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# Hemispheric effects in binocular visual word recognition: Experiments and cognitive modelling

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to

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# Declaration

I hereby declare that this thesis is of my own composition, and that it contains no material previously submitted for the award of any other degree. The work reported in this thesis has been executed by myself, except where due acknowledgement is made in the text.

Mateo Obregón

# Abstract

Functionally, a vertically split fovea should confer an advantage to the processor. Visual stimuli arriving to each eye would be vertically split and the two parts sent to different hemispheres, obeying the crossed nature of the visual pathways. I test the prediction of a functional advantage for the separate lateralisation of text processing from the two eyes. I explore this hypothesis by means of psycholinguistic experimentation and cognitive modelling. I employed a haploscope to show foveated text to the two eyes separately, controlling for location and presentation duration, and guaranteeing that each eye could not see the other eye's stimuli. I carried out a series of experiments, based on this novel paradigm, to explore the effects of a vertically split fovea on correctness of word perception.

The experiments showed: (i) words presented exclusively to the contralateral hemifoveas are more correctly reported than words presented exclusively to the ipsilateral hemifoveas; (ii) the same full word shown to both eyes and available for fusion led to better perception; (iii) word endings with fewer type-count neighbours were more accurately reported, as were beginnings with larger type-count neighbours; (iv) uncrossed-eye stimuli were better perceived than crossed-eye stimuli; (v) principled roles in a model of isolated word recognition for lexical and sublexical neighbourhood statistics, syllabicity, hemispheric fine- and coarse-coding differences, sex of the reader, handedness, left and right eye, and visual pathways. Finally, I propose a connectionist model of visual word recognition that incorporates these findings and is a basis for further exploration.

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This thesis was written with the LyX document processor (The LyX Team, 2009), using Sweave (Gorjanc (2008), Leisch (2002)) to include **R** code (R Development Core Team, 2009) within the LyX document. I have used Catherine Mayo's edthesis2e (Mayo, 1999), with minor modifications, as my base LaTeX class. Furthermore, I have used many Open Source programs in Linux (Debian) to write this thesis. I thank all the Open Source developers for such fantastic work!

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[1] `http://www.hull.ac.uk/RTN-LAB/about/index.htm`

[2] `http://www.ecdf.ed.ac.uk/`, partially supported by eDIKT, `http://www.edikt.org.uk`

# Dedication

I dedicate this Thesis to ...

my son Gabriel and my wife Elizabeth ...

With who I am learning more and more about life

every day.

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# Chapter 1

# Introduction

## 1.1 Aims of the thesis: Binocular visual word perception

We look at words to read them; we can do this in rapid succession, extracting meaning from connected text and making very few errors (after having been exposed to myriads of lines of text). This is recognised as one of our most complex cognitive tasks, and one that most adults can do efficiently and in an automatised manner. Yet, how we even perceive the written word is not clearly understood.

In this thesis I explore this issue with psycholinguistic and statistical tools, starting with the unique anatomical relationship between a single real world, two eyes and two cerebral hemispheres. My experiments are based on a challenging word naming task that explores the perception of a word from letter strings shown to the foveal regions of the two eyes. I rely on observed behaviours of adult proficient readers to differentiate between various experiment conditions.

I undertake an extensive development and application of linear mixed effects regression models to explore behavioural data, relying on anatomical constraints. I conclude by using the results from my experiments to inform a principled model of visual word recognition.

## 1.2 Research carried out for the thesis

### 1.2.1 The question

Brysbaert, Ellis, Lavidor, McDonald, Monaghan, Shillcock and others have argued for a vertically split fovea and its consequent implications for reading. However, others have argued that experiments to date have not been conclusive in showing the existence of a vertically split fovea, and instead opt for the previously-held belief of a bilateral projection from the fovea to the brain (e.g., Rayner, Liversedge, Jordan and Patterson). While Toosy, Werring, Plant, Bullmore, Miller, and Thompson (2001) and Miki, Liu, Englander, van Erp, Bonhomme, Aleman, Liu, and Haselgrove (2001) used fMRI to show a domain-general contralateral preference for vision, the issue of how to test for

specific language effects that are a consequence of the vertically split fovea of two eyes has remained elusive.

### 1.2.2 The hypothesis

From a functional and adaptation perspective, a vertically split fovea would confer an advantage to the processor. Visual stimuli arriving to each eye would be vertically split and the two parts sent to different hemispheres (always obeying the crossed nature of the information: the left visual field would be sent to the right hemisphere, and the right visual field would be sent to the left hemisphere).

Given the over-learned nature of reading, the observed importance of statistical exposure to the written word, and the adaptability and optimisation prowess of the brain, I hypothesised that we should be able to find a functional advantage to having input from the two eyes lateralised and subsequently mediated by the two hemispheres. The aim of my PhD work is to explore this hypothesis by means of psycholinguistic experimentation together with cognitive modelling.

### 1.2.3 My research for this thesis

#### 1.2.3.1 My paradigm: The haploscope

I have constructed a haploscope (a special stereoscope) to show foveated text on a computer screen to the two eyes separately. That is, text was shown in a controlled manner (i.e., screen location and presentation duration), guaranteeing that each eye cannot see what is shown to the other eye. I carried out a series of experiments to test several hypotheses regarding the effects of a vertically split fovea and separate hemispheric effects on word perception.

#### 1.2.3.2 Four letter words: $Both \gg Contralateral > Ipsilateral$

My first set of experiments was inspired by the Toosy et al. (2001) finding of greater contralateral than ipsilateral activation, and was designed to test for a contralateral visual preference in the fovea and for textual stimuli. I tested the hypothesis that letters presented to the temporal visual fields (utilising contralateral pathways to the two hemispheres) –but still within one degree of the vertical cue– would be more accurately perceived than letters presented to the nasal visual fields (utilising ipsilateral pathways to the two hemispheres). I found that the base condition –the same full word shown to both eyes simultaneously– resulted in superior perception over the contralateral and ipsilateral conditions. Furthermore, I found that the contralateral condition was significantly more accurately perceived than the ipsilateral condition, as predicted. In a further experiment I tested to see if the contralateral or ipsilateral conditions correlated with various measurements of reading ability, and found no such associations.

#### 1.2.3.3 Five letters: Conjoint, Crossed and Uncrossed fixation disparity conditions

Binocular eye-tracking researchers have found that people make cross-eye and uncross-eye fixations as well as conjoint fixations during reading. In our lab we have found that most binocular fixations are cross-eyed (Shillcock, Roberts, Kreiner, and Obregón, 2010). My second set of experiments were designed to test whether participants better perceived words shown in crossed, conjoint or uncrossed manners. I used the same haploscope as in previous experiments, but this time the stimuli were made of four letters from the five-letter targets and shown in either conjoint (the letters shown to each eye were superimposed with respect to the fixation cues), crossed (the letters shown to the left eye were shifted left by half a letter and the letters shown to the right eye were shifted right by half a letter) or uncrossed (the letters shown to the left eye were shifted right by half a letter and the letters shown to the right eye were shifted left by half a letter) relative to the superimposed fixation cue in each eye.

Similar to my previous haploscope experiments, the stimuli were shown in either contralateral or ipsilateral arrangements. The two end nasal letters were missing in the contralateral presentations, and the two end temporal letters were missing in the ipsilateral presentations. In the first of these experiments I again found a contralateral advantage with conjoint fixations.

After adding an ipsilateral presentation mode, I found that the uncrossed disparity stimuli were significantly better perceived than the crossed disparity stimuli, contrary to expectations. It became clear that the critical difference was that the crossed conditions and the uncrossed conditions involved a differential overlapping of the letters, depending on contralateral or ipsilateral presentation modes. Specifically, the letters in both the LVF and RVF involved a 2-2 letter overlap or a 3-1 letter overlap relative to the superimposed fixation cues. I found more correct responses in the 3-1 letter overlap cases than in the 2-2 letter overlap cases, whereas in the 3-1 overlap cases I did not find a difference between crossed or uncrossed conditions, in the 2-2 overlap cases I found that the more correctly responded-to uncrossed condition was also the contralateral mode of presentation and the less correctly responded-to crossed condition was also the ipsilateral mode of presentation. There is an ambiguity as to whether the effect observed was due to the uncrossed versus crossed disparity, or due to the contralateral versus ipsilateral mode of presentation of the letters.

#### 1.2.3.4 Beginning and ending hemispheric effects

One consequence of a vertically split fovea would be that foveated words are separated into parts that are initially processed as sublexical forms by each hemisphere; different lines of research have shown complementary traits for cognitive functions associated with

each hemisphere in visual half-field experiments. A set of post-hoc tests on the data from my first experiment showed a tendency for differential processing of the left and right parts of the words, but my target words did not evenly span a range of sublexical forms.

My next experiment tested the hypothesis that statistical properties of the beginning and ending sublexical forms (relative to focus of attention within fixations, for each eye separately) would be processed differently in each hemisphere. I used six-letter targets where the three letter beginnings and endings were shared with other words such that they covered a range of few to many type-count neighbourhood sizes across the lexicon.

I found that words with endings that occurred less frequently were significantly more correctly perceived, as well as words with beginnings that occurred more frequently were significantly more correctly perceived. Thus, I concluded that the LH excels in perception with more unique ending sublexical forms, and the RH excels in perception with more frequent beginning sublexical forms. A range of other variables (i.e., sex, handedness, syllabicity and plural status) were successfully incorporated into the model.

#### 1.2.3.5 A proposal for a computational model

The results from my experiments with the haploscope show a clear mode of cooperation between the eyes and the two hemispheres that optimises their functionality for reading. I propose a Resonance Model that incorporates these functional elements so as to explore emergent properties of such a configuration.

### 1.2.4 Conclusions

My research with the haploscope and challenging single word perception has shown further evidence for a vertically split fovea, with novel findings that the contralateral visual pathways lead to more accurate perception. My second set of experiments with the haploscope contrasted fixation disparity conditions that are observed in binocular eye-tracking and produced corresponding accuracy profiles for single word recognition in conditions of binocular fixation. I have also found that the two hemispheres specialise in complementary manners with regard to the processing of beginning and ending sublexical forms, with the more unique endings (shown to the LH) being better perceived and more frequent beginnings (shown to the RH) being better perceived. In addition, a number of other variables have been incorporated to produce the most complete extant model of visual word recognition.

Overall, I used simple equipment (a four-mirror haploscope with a PC computer) in conjunction with very carefully designed stimuli to generate novel results regarding the processing of visual words by the brain. These in turn shed light on better understanding how the eyes and the brain work together in reading, and I propose a computational model to address this theoretical position.

# Chapter 2

# Literature review

*... crises are a necessary precondition for the emergence of novel theories*

Kuhn (1962)

## 2.1 The contributions of two hemispheres in perceiving foveated words

Our two eyes scan lines of text, fixating on words and extracting meaning in the process; but how word perception occurs is not agreed upon by researchers in the field, even though it has been a key issue of research for many years.

As it has been established that the central part of the visual field is most clearly seen, I will start my review of the literature by expanding on the anatomical constraints of the visual system and how the two eyes connect to the two cerebral cortices. I will explore in detail what we know about how the central part of the retinas –the foveas– connect to the two hemispheres.

As anatomy alone cannot fully inform the functional workings of the brain, I will next review behavioural studies that have been brought to bear on hemispheric properties of word recognition. Most of these studies have relied on showing text away from and to the left or right of fixation location to avoid the perceived confusion regarding the processing of the central visual field. And, while these visual half-field experiments have highlighted separate patterns of responses on language tasks for each visual hemifield, it has remained unclear how text shown in the central visual field is processed.

There are two sets of hypotheses regarding the processing of the central visual field: $(1)$ those that claim that the central region holds a special status different from the rest of the retina and is projected bilaterally to both hemispheres; and $(2)$ those that contend that the central region of the retina has the same connectivity to the hemispheres as

the outer regions of the retina, referred to as the Split Fovea Theory. I will review the recent literature regarding this debate and I will propose experiments and statistical tools to explore visual word perception for text shown at fixation and bounded to within one degree of the central visual field, for each eye separately.

Finally, as computational modelling has been brought to bear on the matter of word recognition as a tool for finding emergent properties and to test novel hypotheses, I will conclude this chapter by reviewing the state of the art in the modelling of word recognition.

## 2.2 Anatomical considerations

While the anatomy of the visual system (including both eyes and the brain), together with behavioural studies, have informed us about general functional properties of visual word perception, they have not managed to uncover the fine detail of its workings.

It is undisputed that we can distinguish shapes and lines most easily and accurately when they are projected onto the foveal region of the retina (see McCann, Hayhoe, and Geisler, 2011, for a recent comparison between foveal and peripheral acuity). This central part of the retina in the back of the eye covers just 1 to 2 degrees of central visual field and contains the highest concentration of ganglion neurons that receive signals from the light-sensitive cone receptors with each cone connecting to 3 or 4 ganglion cells in the fovea (Curcio and Allen, 1990; Curcio, Sloan, Kalina, and Hendrickson, 1990; Perry and Cowey, 1985; Reinhard and Trauzettel-Klosinski, 2003; Wassle, Grunert, Rohrenbeck, and Boycott, 1990). While neuroscientists have shown that the ex-foveal right and left sides of the retina connect to the left and right cerebral hemispheres respectively –for each eye separately–, the question of how the foveal ganglion cells connect to the cerebral hemispheres has not been able to be resolved anatomically (see Kandel, Schwartz, and Jessell, 2000, Chapter 27, for an extensive review).

Staining and behavioural studies have shown that axons from non-foveal ganglion cells travel back through each eye's optic nerve to the medially located optic chiasm, where they are separated such that ganglion cells from the right side of each retina (receiving signals from light receptors stimulated by rays coming from the left visual field, LVF) are firstly connected to the right-side lateral geniculate nucleus and other right-side structures that finally connect to right hemisphere (RH) cortical areas –mostly to the RH primary visual cortex, V1 (see Figure 2.1). Similarly, the left-side ganglion cells (receiving signals from light receptors stimulated by rays coming from the right visual field, RVF) are connected through the optic chiasm to the left-side lateral geniculate nucleus and other left-side structures that subsequently connect to left hemisphere (LH) cortical areas; importantly, this holds for each eye separately. While this anatomical separation of connectivity for the ex-foveal left and right sides of the two retinas is undisputed,

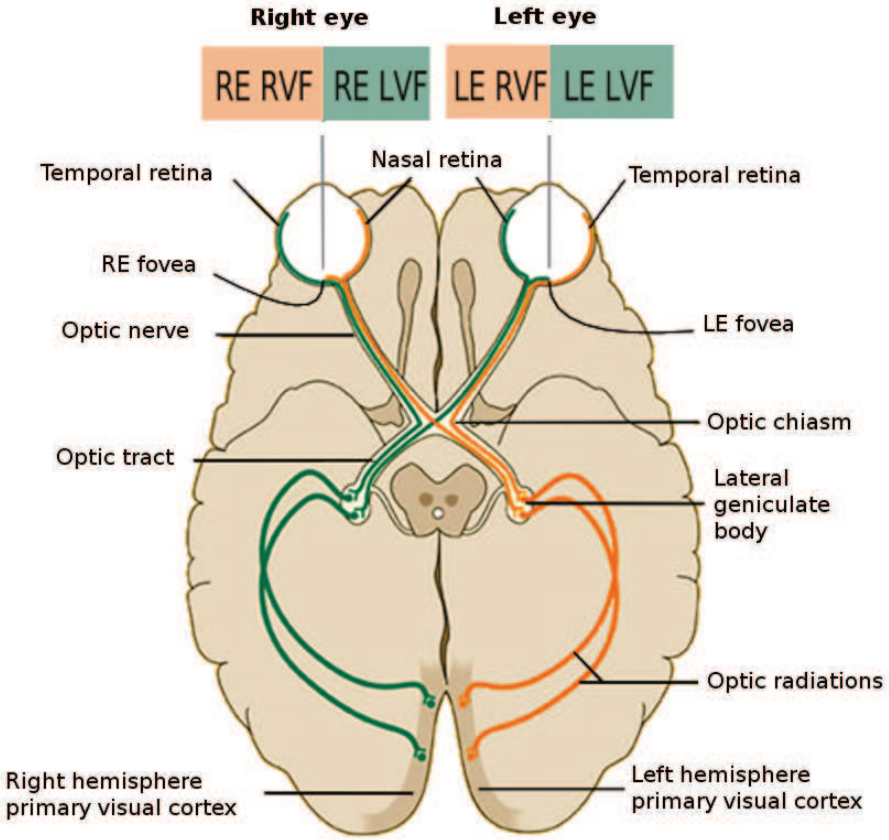


Figure 2.1: Visual Fields, eyes, ocular pathways and cortical structures. A view from below of the anatomical structures involved in vision. Note how each eye has its own Left Visual Field (LVF) and Right Visual Field (RVF), that project onto corresponding temporal and nasal retinas (for each eye separately).

the connectivity of the foveal ganglion cells from each eye to the cortex remains elusive, although we know that the foveal stimulation accounts for upwards of 50% of the occipital V1 areas. Considering that the two eye's foveal regions are responsible for the most detailed account of our visual input, how their respective ganglion cells connect to the cerebral cortex is fundamental to reading.

Previous theories have had the two foveal regions bilaterally connected to both cerebral hemispheres (the bilateral connection theory, BCT), based on evidence from split-brain patients that exhibited macular sparing (see Leff, 2004, for a review). The implication from this concept of connectivity is that foveally attended text (from both eyes) would be projected simultaneously to both RH and LH primary visual cortex V1 areas; hence the signal from the foveated text would always be guaranteed to arrive to the LH that is known to specialise for language. Concomitant with this perspective is the expectancy that both eyes must make conjoint fixations during reading so that

there would be no disparity between the visual streams arriving from the two eyes. I will address this issue in Chapter 4.

The more recent, competing theory is that foveal patterns of connectivity follow in from the outer retinal regions, down to a vertical split within the fovea. That is, the right-side foveal ganglion cells (for both eyes, and receiving signals from LVF) connect to right-side hemispheric structures (like the rest of the non-foveal right-side ganglion cells), and vice versa for the left-side foveal ganglion cells receiving RVF input and projecting to the LH. This pattern of connectivity implies that information from the left and right visual fields travels along separate trajectories to corresponding cerebral cortices in right and left hemispheres: $(i)$ The left eye left visual field $({}^{\mathrm{LE}}LVF_{\mathrm{RH}})$ information crosses the optic chiasm and continues back contralaterally to the RH occipital cortex; $(ii)$ the left eye right visual field $({}^{\mathrm{LE}}_{\mathrm{LH}}RVF)$ is diverted in the optic chiasm and continues ipsilaterally back to the LH occipital cortex; $(iii)$ the right eye left visual field $(LVF^{\mathrm{RE}}_{\mathrm{RH}})$ reaches the optic chiasm and is diverted so that it travels ipsilaterally to the RH occipital cortex; and $(iv)$, the right eye right visual field $({}_{\mathrm{LH}}RVF^{\mathrm{RE}})$ crosses the optic chiasm and travels contralaterally to the LH occipital cortex (see Fig. 3.1). Furthermore, this theory demands that the fovea be vertically divided, and comprises the Split Fovea Theory (SFT). These two hypotheses have led to a lengthy debate between researchers (summarised in Ellis and Brysbaert, 2010b; Jordan and Paterson, 2010; Ellis and Brysbaert, 2010a) that I shall address shortly.

From a bottom-up (visual-features to letters to words) perspective with language primarily localised in the LH, it would be convenient for the complete foveated text always to arrive to the LH primary visual cortex where it would be processed from salient visual characteristics to more abstract invariant lexico-graphic forms (letters), through to a letter integration area (Visual Word Form Area, VWFA, Cohen and Dehaene, 2004; Cohen, Dehaene, Naccache, Lehéricy, Dehaene-Lambertz, Hénaff, and Michel, 2000) where the word item would finally be encoded and thus subsequently used to associate with phonemic and semantic information (cf. Dehaene, Cohen, Sigman, and Vinckier, 2005; Forget, Buiatti, and Dehaene, 2010). Anatomically, the cortical areas would be contiguous or in close proximity within the LH: starting from the V1 representation of the macular retinal ganglion cells to the V4 feature detection areas, outward and upward to the temporal and parietal areas, and reuniting in the temporo-parieto-occipital junction VWFA. The word item would then be passed forward to the LH Wernicke's and Broca's areas containing semantic and phonological processing regions, respectively.

Electrophysiology, magnetoencephalography and brain imaging techniques have shown that many other areas are implicated when participants are performing word recognition tasks, including locations in the RH and the prefrontal cortex (Wheat, Cornelissen, Frost, and Hansen, 2010; Wheat, Cornelissen, Sack, Schuhmann, Goebel, and Blomert,

2012; Cornelissen, Kringelbach, Ellis, Whitney, Holliday, and Hansen, 2009; Holcomb, Grainger, and O'Rourke, 2002; Im, Lee, Jung, and Lee, 2008). In essence, recent evidence is supporting the claim that other regions are simultaneously involved in visual word recognition, and not just the bottom-up schematic from LH V1 to the LH VWFA juncture described above.

Other biological factors have been implicated in reading and word recognition too. Caliskan and Dane (2009) report a study that looked at handedness in 1387 blind (ranging from poor visual acuity to totally blind) and 831 sighted children in Turkey; they found that, while 9.5% of the sighted children were left-handed, 17.7% of the blind children were left-handed. Caliskan and Dane argued that lack of vision could diminish the lateralisation to the left hemisphere. With regard to ocular prevalence and ocular dominance (Kommerell, Schmitt, Kromeier, and Bach, 2003), Fabrizio, Maria, Donatella, and Pierluigi (2011) found no relationship between ocular dominance and reading ability. Hence, while handedness and lateralisation are implicated in blindness, ocular dominance does not appear to relate to word recognition.

With regard to lateralisation of language occurring more strongly in males, Lambe (1999) reported different patterns of fMRI brain activation between male and female participants on word recognition tasks. Lambe also found anatomical differences in post-mortem studies of dyslexics and controls.

Welcome, Chiarello, Towler, Halderman, Otto, and Leonard (2009) measured corpus callosum size for 200 university students (100 male) and tested them on a battery of word tasks. Welcome et al. found that there was an interaction between sex and corpus callosum size: $(i)$ for males, shorter RT with larger corpus callosum size; and $(ii)$ for females, greater accuracy with larger corpus callosum size.

Hsiao and Shillcock (2005) explored naming times and accuracy for Chinese characters that were briefly presented at the location of visual attention. Interestingly, most characters in Chinese have a fixed structure with a semantic component on the left and a phonetic radical on the right. In assuming a vertically split fovea, the phonetic radical on the right of the character would typically be projected to the left hemisphere, and the semantic radical on the left of the character would typically be projected to the right hemisphere; also, some 10% of the characters have an inverted structure, with the phonetic radical on the left and the semantic radical on the right. Hsiao and Shillcock found that males responded more quickly to characters with the phonetic radical on the right (projected to the left hemisphere) than characters with the phonetic radical on the left. However, they found that females reacted equally quickly to the characters with the phonetic radical on the right as characters with the phonetic radical on the left. These results are consistent with males being more lateralised and hence processing the

phonetic radical more expeditiously than females. This research is one of the few that has specifically showed stimuli within the foveal region.

## 2.3 Visual half-field experiments

The lexical processing advantage of the ex-foveal right visual hemifield over the left visual hemifield is long established (Zaidel, Clarke, and Suyenobu, 1990); when a word falls to the right of fixation, it is directly projected to the left cerebral hemisphere (LH), which is typically dominant for language (Brysbaert, 1994; Melamed and Zaidel, 1993). It is generally claimed that the LH tends to specialise in processing expressive phonology (Coney, 2002), syntax (Caplan, Alpert, Waters, and Olivieri, 2000), and visual word-forms (Cohen, Jobert, Le Bihan, and Dehaene, 2004).

As such, this account of visual word recognition has been the main driving force in arguments for bilaterally projected foveas, and the mainstay for what has been described as the right visual field advantage in visual half-field experiments that have shown stimulus material distant from central fixation (to make sure that the stimulus was initially projected exclusively to either the LH or the RH).

For example, Pirozzolo and Rayner (1977) showed that by means of tachistoscopic presentation of words and faces, participants would make more correct responses when words were presented to the RVF (LH) and when faces were presented to the LVF (RH). They argued (as other researchers before them) that this provided evidence for language processing –specifically, word recognition– in the LH. In a second experiment involving a forced-choice from target, visually similar (overall shape, and corresponding letters), "acoustically similar" [sic], and unrelated foil words, Pirozzolo and Rayner found that words presented to LVF (RH) made more visually similar errors than words presented to RVF (LH); they also found that acoustic errors were generally less than visual errors and comparable for both LVF and RVF presentations.

The underlying belief at the time was that this RVF advantage was due to the LH processing of language and that there was little –if any– processing of language in the RH. Gazzaniga exemplifies this approach when he claims in 2009 (quoting research from Benson and Zaidel, 1985 and Zaidel and Peters, 1981), "... while the right hemisphere does have a limited capacity for reading and is able to read whole words (ideographic lexical/semantic access), it is unable to convert graphemes to phonemes, as can the language-dominant left hemisphere." (Gazzaniga and Miller, 2009, p. 264)

For text shown in the LVF and projected to the RH, researchers argued that cortical areas in the RH would project back through the corpus callosum to the LH so that the visual information could be decoded into words. Dehaene et al. (2005) typified this view, arguing that that RH could act separately up through the identification of abstract letter features (V4 and V8), but then this information would be projected across

the corpus callosum to the LH occipito-temporal sulcus where open bigrams would be initially encoded.

Yet, in the 1980s other researchers proposed that the RH participated in word recognition in a manner different to the LH. Bub and Lewine (1988), for example, proposed that the LH performs a parallel processing of letters in the RVF, while the RH performs a sequential processing of letters, and hence why longer words in the LVF taker more time to be categorised.

More recently, researchers have found differences between LVF and RVF word recognition in word length, case alternations, and orthographic neighbourhood size, among others (Ellis, Ansorge, and Lavidor, 2007). There has also been room for disagreement between the interpretation of results showing words exclusively to LVF or RVF (Deason and Marsolek, 2005). However, while all these results inspire an account whereby the LH and RH have different roles in word recognition, they do not address the issue of what is processed by foveally presented stimuli.

Beeman (2005) presented a range of experiment results and neurological arguments in favour of separate processes in both hemispheres for the comprehension of natural language. In particular, they laid out the argument that word activation, selection and integration have counterparts in both hemispheres that interact among themselves and across hemispheres. They described the LH as contributing with more fine-grain presses –small and focused semantic fields– and the RH as contributing with coarse-grain processes –large diffuse semantic fields.

While Beeman (2005) subsumed word recognition within the larger process of understanding natural language, their division of labour between the two hemispheres and their characterisation of coarse-grain and fine-grain process equally applies to visual word recognition. The question remains if their characterisation of coarse-grain processing for RH and fine-grain processing for LH could be applied to just foveally presented words.

## 2.4 Issues around a vertically split fovea

As described above, the human fovea has often been considered to project directly and simultaneously to both hemispheres, but behavioural evidence has accumulated, along with computational and neuropsychological theorising, to suggest that the fovea shares the vertically divided structure of the rest of the retina, known as the split fovea theory (Brysbaert, 2004; Corballis and Trudel, 1993; Ellis and Brysbaert, 2010b; Lavidor and Walsh, 2004; Luo, Shan, Zhu, Weng, and He, 2011; McDonald and Shillcock, 2005; Monaghan, Shillcock, and McDonald, 2004; Shillcock et al., 2010; Shillcock, Ellison, and Monaghan, 2000).

As the most recent vocal critics of the split fovea theory, Jordan and Paterson have argued against the experiments that claim to support the split fovea theory, rather than

the theory itself (see Jordan and Paterson, 2008, 2010; Jordan, Paterson, and Stachurski, 2009, for a recent overview). In particular, they argue that knowing the precise fixation location of the eyes is fundamentally important (e.g., with an eye-tracker), as well as pointing out that behavioural studies with brain lesion patients (eg, Corballis and Trudel, 1993) do not provide an adequate testing ground for the split fovea theory.

While using an eye-tracker to localise eye-fixations might improve fixation location accuracy in an experiment, the error margin for typical eye tracking equipment is around 0.5 degree (SR Research specifications for the head-mounted EyeLink 1000, retrieved on the $19^{th}$ of June 2012 from `http://www.sr-research.com/EL_1000.html`), which is almost half the size of the foveal field of view. On the other hand, methodological paradigms that randomise many item presentations per participant would statistically cancel an artefact arising from location of attention. Most of the recent split fovea theory studies have used this technique (eg, Brysbaert, 2004, 1994; Brysbaert, Cai, and Van der Haegen, 2012; Cai, Paulignan, Brysbaert, Ibarrola, and Nazir, 2010; Van der Haegen and Brysbaert, 2011; Hsiao and Shillcock, 2004a,b, 2005; Lavidor, Ellis, Shillcock, and Bland, 2001; Lavidor, Hayes, Shillcock, and Ellis, 2004; Monaghan et al., 2004; Obregón and Shillcock, 2012; Hunter, Brysbaert, and Knecht, 2007).

From an optometric point of view, Reinhard and Trauzettel-Klosinski (2003) showed, using the most accurate scanning laser ophthalmoscope technology available, that the vertical division of the fovea may vary between very precise division (no overlap) and 0.6°. While Reinhard and Trauzettel-Klosinski projected light points at different eccentricities onto the retinas of hemianopic patients who reported seeing or not the stimuli, Jordan and Paterson (2010) argued that only one side of the "foveae" could be mapped for these patients, and that the other side of the fovea could project bilaterally.

Regarding behaviour evidence for the split fovea theory, Lavidor et al. (2004) reported differential effects of lexical neighbourhood based on statistics calculated separately for the left and right halves of centrally-fixated six-letter words. Also, Hsiao and Shillcock (2004a; 2005) reported that centrally-fixated single Chinese characters with different left-right semantic/phonological structures result in naming-time differences that are predicted on the basis of foveal splitting. While these experiments do not avoid Jordan and Paterson's critiques that fixation location was not guaranteed, the experiment materials were randomised in a within-participant design that would make any horizontal offset in fixation location contribute as random noise to the data.

Syllable frequency for the first syllable (i.e., the number of words that share a syllable at the start of the word) has been found to be important in lexical decision tasks, both for shallow orthography languages (e.g., Álvarez, Carreiras, and de Vega, 2000, for Spanish) as for deep orthography languages (e.g., Hutzler, Bergmann, Conrad, Kronbichler, Stenneken, and Jacobs, 2004, for German). The general finding is summarised as an

inhibitory effect: larger frequencies for the first syllable induced longer RT. In these studies, target words were centred at fixation implying that –assuming the split fovea theory– the beginning of the word (containing the first syllable) would be projected to the RH. However, target words were displayed until response, so participants had opportunities to refixate the longer multisyllabic words that did not fit into exclusively into the fovea.

Toosy et al. (2001) described an fMRI study showing that monocular stimulation causes significantly greater and more extensive occipital lobe activation in the contralateral hemisphere than in the ipsilateral hemisphere. That is, the right eye causes greater activation in the LH than does the left eye in the LH, and the left eye causes greater activation in the RH than does the right eye in the RH. Toosy et al. offer several potential contributing explanations: unique contralateral representation for a crescent of the temporal hemifield (Horton and Hocking, 1996); greater retinal ganglion cell density in the nasal retina (Perry and Cowey, 1985); a bias towards crossed fibres at the optic chiasm (Kupfer, Chumbley, and Downer, 1967) and the lateral geniculate nucleus (Chacko, 1948); organizational bias in the ocular dominance columns in V1 towards contralateral input (LeVay, Connolly, Houde, and Van Essen, 1985); and greater contralateral contribution to the activity of V1 cells with a binocular receptive field. Additionally, there is evidence for greater activation corresponding to the functionally dominant eye (Rombouts, Barkhof, Sprenger, Valk, and Scheltens, 1996). Thus, as well as the long-recognised contralateral and ipsilateral projections of the ex-foveal hemiretinas, there is a bias towards a contralateral projection at the level of the whole eye (see also Miki et al., 2001).

While Toosy et al. used full-field photic stimulation of each entire eye, stimulating just the fovea would be very complicated. Indeed, the monocular crescent exclusively available to each eye, as well as the blind spot, concern only non-foveal parts of the retina. The critical question remains whether Toosy et al.'s findings of advantaged contralateral projections apply to the processing of foveated targets.

In this thesis I examine evidence for a functional contralateral bias specifically within the fovea. I predict a contralateral behavioural bias for foveal stimulation, based on the coordination of the hemifoveas across the two eyes when reading isolated words. The precise vertical splitting of the human fovea allows for detailed predictions for foveally presented lexical stimuli in conjointly and non-conjointly fixating eyes (Shillcock et al., 2010): for visual stimuli falling within the fovea for each eye, the two temporal visual hemifields (contralaterally projected) should be advantaged over the two nasal visual hemifields (ipsilaterally projected).

## 2.5 Experiment paradigm and statistical modelling

### 2.5.1 Testing for foveal input

The issue of how to test for a vertically split fovea remains elusive. Clearly, experiments with both eyes looking at the same general stimuli does not guarantee separate hemifoveal stimulation; a new paradigm is required.

Forget, Buiatti, and Dehaene (2010) found that participants could easily perceive a word from alternating letters on two screens presented in rapid succession. They found that for ISI durations below 80 ms, participants could merge the letters to correctly classify the target in a lexical decision task; in all cases, the screens with letters were visible for only 16 ms, and followed by a full-length '#' back-mask.

Together with the presentation of stimuli separately through a stereoscope Kleiven and Rommetveit (1970); Rommetveit, Berkley, and Brøgger (1968a); Rommetveit and Blakar (1973); Rommetveit and Kleiven (1968); Rommetveit, Toch, and Svendsen (1968b), nonword stimuli could be shown to the two eyes separately such that the combination of the input from the two eyes would constitute a proper word. A critical test for this paradigm could be to find a contralateral preference described by Toosy et al. (2001) and Miki et al. (2001), described above, for stimuli presented within the perimeter of the fovea.

### 2.5.2 Statistical modelling

Statistics in psychology has made great strides recently, moving from comparing group means for experiment conditions to experiment designs with crossed random effects for participants and materials; Such is the importance of these changes that the journal of Memory and Language in 2008 dedicated a full issue to the application of these modern statistical methods to cognitive psychology (cf., Forster and Masson, 2008). This has come about largely because of the need to address the large variability between people, especially when we are looking at cognitive function, as group comparisons on experiment manipulations only reveal statistically significant differences when the experiment manipulation produces large differences, larger than the between-participant variability.

One of the initial efforts to address the large between-participant variability was to calculate ANOVA F ratios for experiment and participant separately, and then divide these two to obtain a criterion value. However, Clark (1973) pointed out strong deficiencies in this method (treating target items and then participants as fixed effects), and devised the minF' method to place bounds on participant variability. Nevertheless, experiment paradigms that relied on this statistical finesse layered on top of the ANOVA remained inherently limited in that they nevertheless were not correctly identifying all the random effects sources of variability.

As the field of statistics advanced to take advantage of more computer power (for example, in the form of Montecarlo methods for evaluating probabilities), together with theoretical advances in statistics that demonstrated that the famed and trusted ANOVA was just a special case of the more general linear regression analysis, new computational approaches were proposed. With computers managing to manipulate large matrices, a previously specialised procedure called Maximum Likelihood (ML) estimation could be applied to find the coefficient values in regression models, in effect carrying out a Type III analysis of the error (cf., Baayen, Davidson, and Bates, 2008a; Dixon, 2008; Harville, 1977; Jaeger, 2008; Pinheiro and Bates, 1995; Quené and van den Bergh, 2008).

While a Maximum Likelihood analysis can be computationally expensive, the faster Restricted Maximum Likelihood (REML) procedure could be used instead of ML, with the benefit that the REML procedure is more robust to random effects terms (Pinheiro and Bates, 2000).

Furthermore, and moving beyond the ANOVA limitations requiring a normal error distribution and comparable standard deviations between groups (treatments), the more general linear regression method with REML estimation could use different functions to model the error in the dependent variable; apart from from the standard Gaussian distribution, binomially distributed data could be analysed with logistic curves, count data could be analysed with Poisson distributions, and data with extinction error distributions could be modelled with a Gamma function.

Most importantly, the general linear regression analysis can have an arbitrarily complex structure of nested predictors and random effects terms, as long as there is enough data in all the possible cases to allow for the calculation of the REML estimation for all the model terms. Furthermore and unlike the ANOVA, treatment groups are not required to have the same number of cases. This meant that missing data and uneven distribution of participants between experiment conditions were not major issues. These models with random terms are known as Linear Mixed Effects Regressions (LMER).

With the popularisation of the public domain R scripting language that includes specialised libraries for statistical analysis (Allerhand, 2011; R Development Core Team, 2009; Baayen, 2009; Bates and Maechler, 2009), cognitive scientists have being increasingly using LMER modelling in cognitive psychology research (Baayen, 2008, 2009; Baayen, Davidson, and Bates, 2008b); this trend will be more pervasive with books that specifically aim to make generalised linear regression models more understandable for the non-specialised statistics user (e.g., Field, 2009; Field, Miles, and Field, 2012; Grafen and Hails, 2002). I have followed the development of these statistical methods and I have extensively used Linear Mixed Effects regression modelling in the research contained in this thesis. A general description of my strategy for the analysis of the data I collected for this thesis can be found in Section 3.6.2.

## 2.6 State of the art: Computational models

Ever since the first days of computers, computational models of word recognition have been developed to attempt to elucidate and inform our understanding of how it is that we recognise visually presented words. Most attempts through the 1990's implemented and expanded the box-and-arrow models proposed by the early 1900 neurologists, who hypothesised that specific locations in the brain corresponded with specific cognitive functions (and hence the apparent appropriateness of the box-and-arrow approach for mapping boxes to functionality and then to brain localisation). Coltheart, Curtis, Atkins, and Haller (1993) and Seidenberg and McClelland (1989) typified this approach, each group arguing that their dual route or parallel distributed processing approach (respectively) was the more apt to illuminate how the brain carries out the task of perceiving a visually presented word and transforming it into a phonological item to be read out aloud. As most other researchers of the time, they compared the performances of their models to human performance, mostly on naming and lexical decision tasks.

Jacobs and Grainger (1994) summarised these and other models in a special section of the Journal of Experimental Psychology: Human Perception & Performance dedicated to models of visual word recognition (Vol. 20(6), December 1994). Jacobs and Grainger claimed that the field was in a state of instability at the time, with complex (macro) modelling efforts competing with simple (micro) models. They argued that all the models of word recognition should inform a single "unified theory" that could explain results from behavioural and brain imaging, multiple language domains, development and pathological domains. As such, much of their article was dedicated to the grouping of models, and specifically, what variables should be used to judge models. Jacobs and Grainger presented their meta-analysis in a table (Jacobs and Grainger, 1994, p. 1313) where all the models they reviewed (the then "state of the art" models) were evaluated in terms of percent correct and reaction time for lexical decision, naming time, or perceptual identification (each model covered different subsets of these measures). Moreover, several psycholinguistic parameters were considered, namely, the frequency effect, the word superiority effect, the orthographic neighbourhood effect and the regularity/consistency effect. Jacobs and Grainger concluded that more work had to be done, as no model explained all the effects observed in humans in terms of the measures they proposed; they finalised their overview by claiming that any new model should be able to account for what all the previous models could explain.

While phonology, semantic codes and functionality featured prominently in the models reviewed by Jacobs and Grainger, none of these models of visual word recognition considered anatomical information such as having two eyes that connect separately to the two hemispheres. At most, some of the macroscopic models included a module

receiving retinal activation and eventually producing words (e.g., Grossberg and Stone, 1986 with a "visual object recognition system"; Rumelhart and McClelland, 1982 with "feature level", "letter level" and "word level" nodes; Coltheart et al., 1993 with "visual feature detectors", "letter detectors" and "word detectors").

The main objection for me with respect to the Jacobs and Grainger (1994) review is that mimicry of human cognitive function does not ensure that the methods internal to the model relate in any way to the algorithms driving human behaviour, as so aptly exposed by Braitenberg (1986) with his "vehicles" that move around with just a few simple commands, but appear –to the naïve observer– to be "interacting" in complex psychologically plausible manners.

Current efforts in modelling of visual word recognition have left aside the Jacobs and Grainger's (1994) requirement of including all the outcomes from previous models, and instead have concentrated on producing models that cover an idealisation of: $(i)$ of the distributional properties of a lexicon (e.g., Baayen, Milin, Đurđević, Hendrix, and Marelli, 2011; Norris, 2006, 2009); and $(ii)$ computational complexity for arriving at a word form (e.g., Hannagan and Grainger, 2012; Grainger and Ziegler, 2011; Stevens and Grainger, 2003). These new models remain abstract –pertaining to sequences of letter tokens– and do not take into account anatomical aspects of visual word recognition such as having two eyes. Their current aim is to provide exemplary evidence of how the brain could resolve letter tokens into word items.

Baayen et al. (2011) generated co-occurrence probability matrices derived from the application of the discriminative learning Rescorla-Wagner algorithm (Danks, 2003) to words. Baayen et al. argued that their "naive discriminative learner" was parameter-free because it was solely based on a corpus of words and was not fitted to human behaviour (although they did include a parameter to adjust for longer words that are typically fixated multiple times). They then compared results from primed lexical decision tasks to their prediction model on typical psycholinguistic constructs such as morphemic structure and word frequency. While they found a high level of fit between their prediction model and human behaviour, they concluded, "... [the "naive discriminative learner"] provided precision and model simplicity; [but] the disadvantage is 'explanatory disappointment' " (Baayen et al., 2011, p. 475). As human languages have developed over time with usage, a "naive" analysis of their tokens will reflect how humans use the languages. Hence, the Baayen et al. model is an explanatory disappointment in that it does not "provide higher order explanatory principles" (ibid.) for the workings of the brain.

Norris (2006) instantiated a computer program that effectively manipulates strings of letters and produces "behaviours" that are comparable to a range of psycholinguistic observables, including word frequency, word neighbourhood effects (and interactions with other terms), lexical decision times and word identification. Their hypothesis is

that human brains approximate an ideal Bayesian machine, and hence why Bayesian statistics would be an appropriate tool to instantiate cognitive function. They justified their goal of producing optimal behaviour in terms of the concept of an "ideal observer" (amply used in vision research, cf. Geisler and Kersten, 2002) given a perceptual input and a clear specification of the task to be performed, produces an optimal behaviour.

While neighbourhood size effects for whole words have shown a LVF (RH) advantage in lexical decision tasks (see Andrews, 1997, for a review), Whitney and Lavidor (2005); Whitney (2004a,b) argued that these results could be manipulated by modifying the relative features of the letters in the target. Whitney instantiated this in the SERIOL computational model for word recognition (Whitney, 2001, 2008), claiming that it is the individual letter features (and therefore the individual letters) that are important for word recognition.

Hannagan and Grainger (2012) have used computationally eloquent String kernel methods to process letter tokens into words. They argued that String kernel methods "... are virtually identical to one contending proposal for how the brain encodes orthographic information during reading" (Hannagan and Grainger, 2012, p. 575). However, they follow an approach characterised by combining letters into "open bigram" pairs (Conrad, Carreiras, Tamm, and Jacobs, 2009; Whitney, 2001, 2008; Whitney and Cornelissen, 2008; Whitney and Lavidor, 2004, 2005), arguing that the tempo-parietal juncture in the LH and hypothesised to be a visual word form area (Cohen and Dehaene, 2004) would use a process analogous to String kernels to take open bigrams and produce word tokens that optimally match.

While much of the modelling efforts described above were concerned with monosyllabic word recognition, Yap and Balota (2009) used regression analysis to explore the pronunciation and lexical decision times of 6115 monomorphemic multisyllabic words. As they point out from Perry, Ziegler, and Zorzi (2007), "Although most of the words people read are monosyllabic according to a token count, the majority of the words in the lexicon are polysyllabic according to a type count." (Perry et al., 2007, p. 304). Thus the understanding that visual word recognition of multisyllabic words "is clearly an important next step for the field." (Yap and Balota, 2009, p. 527) Yap and Balota found that they could explain almost 62% of the variance in their two dependent variables, fitted by a wide range of measures regarding frequencies, neighbourhoods, syllabicity, and distance metrics, among others. They situated their efforts as a reference point for future models of monosyllabic and multisyllabic visual word recognition, positing statistical regression methods as a key tool for capturing the complexity of visual word recognition.

Shillcock and Monaghan (2001) proposed a computational model that embodied the concepts of a vertically split fovea and two hemispheres. They trained their connectionist model with word lists that were successively staggered across two input vectors corresponding to left and right hemifoveas and connected separately to two middle layers representing the two hemispheres. They found that their model reproduced the special nature of the exterior letters of words in recognition. Monaghan and Pollmann (2003) took the modelling of hemispheric effects further to show that complex tasks (e.g., naming two letters with the same name) were more correctly performed when the stimuli were shown to both hemispheres as opposed to the same hemisphere.

Each of these researchers has made valuable contributions to the field, and as such we know a lot more about visual word recognition by having constructed computational and statistical models that test for different hypothetical factors purported to be important to word perception. My personal approach to modelling visual word recognition is to avoid the explicit inclusion of isolated formal linguistic constructs –like letters and words– and instead instantiate these constructs as entities tied down to anatomical distinctions in the model.

## 2.7 Four critical questions regarding visual word recognition

1. Can a linear mixed effects statistical modelling paradigm capture the increasing complexity of the processing required for visual word recognition?
2. Can we build a theoretical model that incorporates detailed anatomy and does not rely on abstract letters and words?
3. Can the Split Fovea Theory be the basis for such a model?
4. Can such a model be the basis for a cross-linguistic tool, covering pictographic as well a lexicographic languages?

# Chapter 3

# Using a haploscope to explore word perception, split-fovea and hemispheric issues

## 3.1 Chapter overview

The experimental work I describe here will address the perception of single four letter words presented dichoptically and for extremely short durations. I will test the hypothesis that words presented to contralateral hemifoveae (as two half-words) are more likely to be correctly identified than when the half-words are presented to the ipsilateral hemifoveae, as predicted by the combination of a contralateral visual advantage and the split fovea hypothesis, but not by the bilateral fovea hypothesis. I analyse the data provided from my novel experimental set-up with Linear Mixed Effects regression analysis.

## 3.2 Introduction

Given two eyes, there are four visual hemifields that project to the occipital cortices of the left and right hemispheres. According to the split-fovea hypothesis, each of these visual fields extends into the foveae and fall onto separate surfaces that are connected independently to each of the two hemispheres. That is, while the Left Visual Field (LVF) of the Left Eye (LE) is connected exclusively to the Right Hemisphere (RH) [labelled as ${}^{\mathrm{LE}}LVF_{\mathrm{RH}}$; see Figure 3.1], the Right Visual Field (RVF) of the same Left Eye is connected initially and exclusively to the Left Hemisphere (LH) [labelled as ${}^{\mathrm{LE}}_{\mathrm{LH}}RVF$]. In a similar manner, the LVF and RVF of the Right Eye (RE) are each connected exclusively to the RH and LH, respectively [labelled as $LVF^{\mathrm{RE}}_{\mathrm{RH}}$ and ${}_{\mathrm{LH}}RVF^{\mathrm{RE}}$]. The nerve fibres from each of the two foveae first travel to the optic chiasm situated behind the eyes, where they are separated in two, according to their nasal or temporal origin; then these divided optic nerve tracts continue back to left and right Lateral Geniculate Nuclei (LGN) below the two hemispheres such that the left LGN receives both RVFs from the two eyes, and the right LGN receives both LVF from the two eyes. The separation of the optic nerve at the optic chiasm has the dual effect of $(i)$ making the nasal visual fields (temporal hemifoveae) connect to the hemispheres on their same side (i.e., ipsilaterally), and $(ii)$

making the temporal visual fields (nasal hemifoveae) connect to the hemispheres on opposite sides from the visual fields (i.e., contralaterally).

Many neurological experiments and anatomical studies have shown the existence of these separate pathways for the left and right retinal areas outside of the fovea. Yet, there has been much debate on whether and how far this left-right visual field separation extends into the fovea.

I tested the Null Hypothesis that both hemifoveae contribute equally to the processing of the relevant stimulus, implying that the Contralateral and Ipsilateral experiment conditions would result in equally accurate recognition scores for briefly presented words. This view would be consistent with a bilateral projection from the fovea.

In fact, I predicted that participants would be more likely to recognise a word in the Contralateral condition compared with the Ipsilateral condition. This pattern would be consistent with a vertically split fovea. A secondary prediction was that whole words presented simultaneously to both eyes (the Both condition) would produce the most accurate recognition scores (c.f., Justo, Bermudez, Perez, and Gonzalez, 2004).

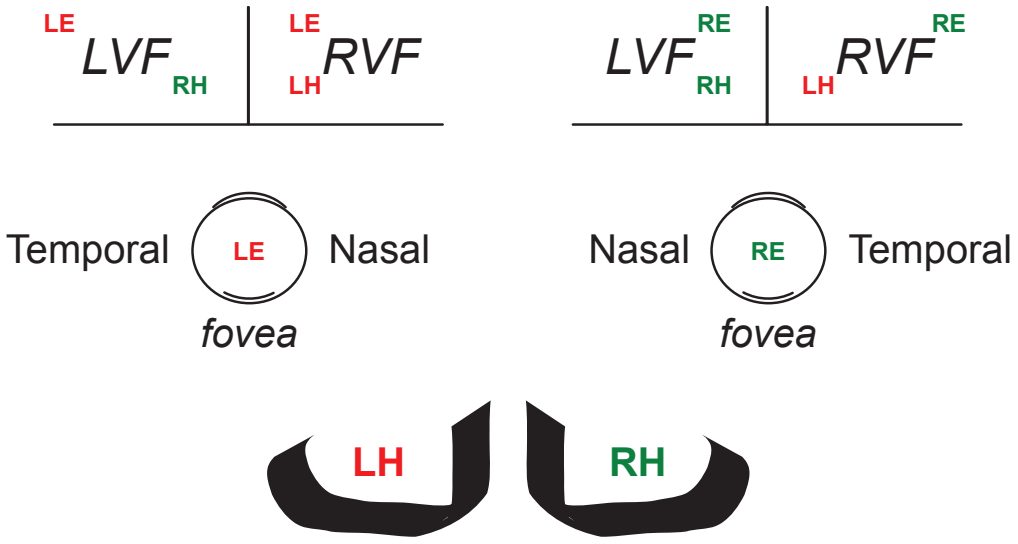


Figure 3.1: Schematic diagram showing the terminology I use for the ocular system. LE (Left eye); RE (Right eye); LH (Left Hemisphere; RH (Right Hemisphere); and the Temporal and Nasal directions. The four visual hemifields resulting from having two eyes are labelled according to what visual field areas are connected to which hemispheres: ${}^{\mathrm{LE}}LVF_{\mathrm{RH}}$, ${}^{\mathrm{LE}}_{\mathrm{LH}}RVF$, $LVF^{\mathrm{RE}}_{\mathrm{RH}}$, and ${}_{\mathrm{LH}}RVF^{\mathrm{RE}}$.

One very pertinent experiment that showed a contralateral advantage was conducted by Toosy et al. (2001), where they monocularly stimulated each eye separately in an fMRI paradigm. Since the whole eye was stimulated with a low intensity light, both hemispheres were subsequently activated. Toosy et al. measured voxel intensity levels in

the left and right striate cortices after stimulation of each eye and subtracted activation levels originating from LE stimulation from the activation levels from RE stimulation, for each cortex separately. Toosy et al. found (for all 15 participants) greater levels of cortical activation from contralateral visual stimulation than from ipsilateral visual stimulation. However, their experimental paradigm stimulated the whole eye and so it is not possible to assert anything specific about foveal processing from this experiment.

To test for a contralateral advantage for foveal regions, the given layout of the four visual fields allowed me to manipulate the presentation of visual information that subsequently arrived to the two hemispheres. By projecting different text in each of these distinct hemifoveal fields, I could explore the consequences of the stronger contralateral cortical activation that Toosy et al. found.

I controlled for eye movements in my experimental paradigm by limiting the time that participants had to observe the stimuli, ensuring that they did not have sufficient time to refixate the text (and thereby possibly having the stimuli present in a different visual field from that which I intended). To determine the maximum amount of time that I could show stimuli before participants would move their eyes, I ran a pilot study where I showed ten participants my stimuli at presentation durations ranging from 57 to 157 ms.[1] I found that with 100 ms (or more) presentation durations participants would report that the two stimuli shown to the two eyes separately would appear overlapped and not contiguous, as they should appear by the way I placed the text on the screen in the haploscope. Consequently, I devised a methodology that combines a haploscope with text presented on a computer screen for durations that are shorter than 80 ms. The targets were briefly presented as half-words to different visual fields such that they would appear as a single whole word in a perceptual recognition paradigm.

## 3.3 A divided-fovea experimental paradigm

I constructed a haploscope (a special mirror stereoscope, see Figure 3.2) to project single four-letter words dichoptically.[2] A fixation cue consisting of a vertical line with an opening in the middle (where the target stimulus would subsequently be presented) was shown to each eye separately and in the centre of the eye's field of view. The participant would then press two buttons with both hands to signal that they were focused on and attending the blank space in the middle of the clear vertical cue. If the cue was not stereoscopically viewed, a double image would be perceived by the

[1] McDonald, Carpenter, and Shillcock (2005) used the Dundee eye-tracking corpus (Kennedy, 2003) to determine that adult observers mostly took between 175 and 200 ms for fixations in reading text presented on a computer screen. Also, Salthouse and Ellis (1980) found that their four participants could discriminate vowels presented for 80 ms with an accuracy of about 99%.

[2] My follow-on experiments used five and six letter words as stimuli.

participant; hence I instructed them to try to "have a clear image of the vertical cue before pressing the two buttons".[3]

I then presented left and/or right halves of target words to specially chosen hemifoveal fields for the right eye and the left eyes. Thus, whole words were presented foveally in one of three experiment conditions: (a) a Both condition, where the whole word was presented to both eyes simultaneously; (b) a Contralateral condition, where the target word was divided into two bigrams and presented in only the temporal hemifoveal fields of both eyes, and (c) an Ipsilateral condition, where the two halves of the target word were shown in only the nasal hemifoveal fields of both eyes. Figure 3.3 shows a schematic diagram of how stimuli presented to the hemifoveal fields are projected to the the visual cortices. All stimuli were shown horizontally within 0.48 degree from the position of the fixation cue in the viewing window for each eye.

As each eye receives separate information, the letters were projected to either contralateral or ipsilateral hemispheres. In all cases the left bigram is passed to the right hemisphere and the right bigram is passed to the left hemisphere, as is expected in normal conditions of centrally fixating a word; it is the provenance of the half-words that varies across Contralateral and Ipsilateral conditions.

The next part of my experiment is to compare performances for the three experiment conditions. Different researchers have used the concept of "probability of correct word recognition" (e.g., Nazir, 2000). Also, Garner and Haun (1978) found that degraded letters can still be identified, albeit with greater difficulty. Hence, I chose to compare my experiment conditions by means of a probability of correct word identification with challenging a experiment task such that participants made errors.

After several pilot explorations with the haploscope (described below), I ascertained that participants perceived dichoptically presented half-words –in both Contralateral and Ipsilateral modes of presentation– as a single four-letter word when the stimuli was on the screen for less than 80 ms. Consequently, I designed an experiment that required participants to correctly identify a four-letter lexical target presented for a very short duration (to make the task hard, for 14, 28 or 57 ms, depending on a pretest) followed by a six-letter back-mask of hashes to confound any retinal image perseveration. Again, the stimuli were shown at this extremely short duration so that the participant did not have time to re-fixate the target, but also to put the participant under maximal processing pressure.

[3]I had two participants in this experiment who experienced diplopia (where one of the eyes was looking somewhere different from the cue and hence caused a "double image") and were consequently not tested.

## 3.4 The mirror haploscope

I constructed a mirror haploscope using four high quality experimentation mirrors and two large tubes (that acted as a septum) which led from the mirrors to two areas of the computer screen where the target items were presented (Figure 3.2). The mirrors and tubes were inside a mat black box and hidden from the participant. The experiment took place in a quiet and darkened room.

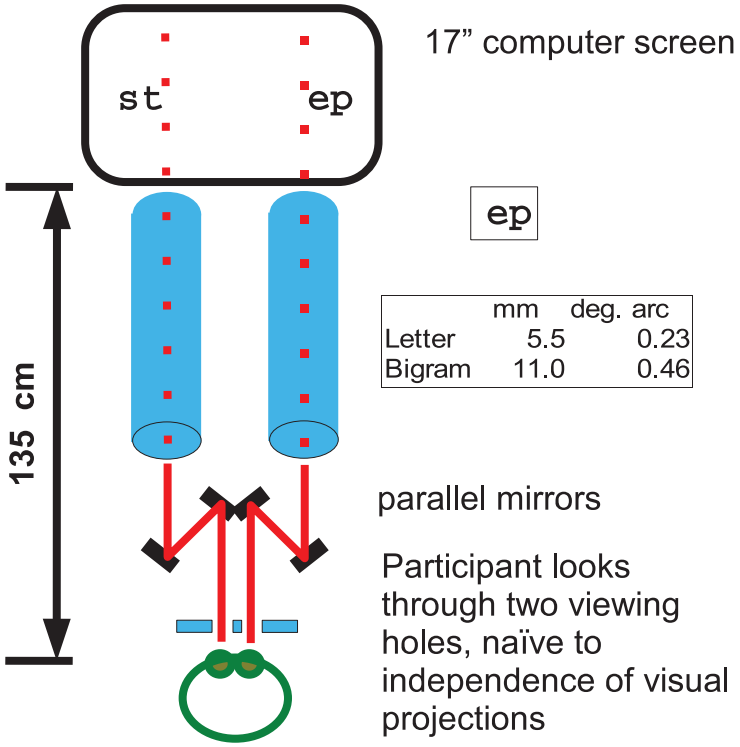


Figure 3.2: Schematic diagram of my mirror haploscope. An example of the target word "step" is shown in the Contralateral condition, where the beginning bigram is displayed to the left of the preceding cue for the left eye, and the ending bigram is displayed to the right of the cue for the right eye (${}^{\mathrm{LE}}LVF_{\mathrm{RH}}$ and ${}_{\mathrm{LH}}RVF^{\mathrm{RE}}$, respectively). A full four-letter word occupies 0.934 degrees of arc, small enough to fall wholly within the fovea.

The participant only saw two apertures in the black box that led back to the monitor 135 cm away. When they looked through the apertures, they saw whatever was shown in the two separate areas of the computer screen (guaranteed to be separate by the tubes that acted as a septum). The participants were unaware that they were seeing separate regions of the computer monitor with each eye.

The stimulus text was shown using a grey (RGB: 190,190,190) Bold Courier New 24 point font on a 15" (32 cm by 24 cm display area) natural flat .25 pitch Vision Master Pro 413 IIYAMA monitor against a completely black background. The display was connected to a dual head Matrox 450 graphics card operating at 70 Hz (1024 by

768 pixels, with a 16 bit colour depth) resulting in the screen being completely redrawn every 14.28 ms.

## 3.5 Hypothesis

With the two halves of words presented simultaneously and separately to the two eyes in a spatially correct order and for very short durations, people will recognise the target word as the combination of the two halves. Within a repeated-measures paradigm, each participant will see one third of the targets in the contralateral visual fields and one-third in the ipsilateral visual fields (see Figure 3.3). The remaining third will be shown completely and simultaneously to both eyes to ensure that participants can identify the words under these short duration conditions and also to provide a baseline.

My hypothesis is that the Contralateral and Ipsilateral experiment conditions project separately to the two cerebral hemispheres and thus will have separable effects for each hemifovea that is stimulated. The Null Hypothesis will be that word recognition probability will not be different between the Contralateral and Ipsilateral experiment conditions. A difference in favour of either Contralateral or Ipsilateral presentations will validate the concept of a split-fovea effect in processing; furthermore, I predict that the Contralateral condition will be more likely to be correctly perceived.

## 3.6 Exp. I. Four-letter words in Both, Contralateral and Ipsilateral conditions

### 3.6.1 Methods

#### 3.6.1.1 Participants

Participants signed an Informed Consent form and were paid at minimum wage levels for their participation; the experiment lasted roughly 30 minutes. I tested English speaking university students and graduates who had "normal or corrected-to-normal vision" in both eyes.[4] I excluded from my analysis those that did not fully meet my criteria.

#### 3.6.1.2 Design

The experiment was carried out within a repeated measures paradigm: a total of 108 words were shown to each participant, comprised of three experiment conditions ("Both", "Contralateral" and "Ipsilateral", see Figure 3.3) and two word frequency groups (low, high). There were 18 stimuli in each condition-by-frequency cell. The materials were counterbalanced in a Latin Square design and the experiment was administered in two parts with a short break in the middle (to permit the identification of any fatigue or facilitation effects across the two sessions).

[4] I also tested for possible differences between glasses, contact lenses and normal eyes.

I selected the target four-letter words from the MRC psycholinguistic database (Wilson, 1988), from low and high frequency ranges after excluding inappropriate words. The visual stimuli were then generated from the target words and prepared for presentation in the haploscope (described on page 24) by means of an AWK script (written by me) that generated a representation of each target for the Both, Contralateral and Ipsilateral conditions. These were then randomised and assigned to each of three Latin Square lists and included in an E-Prime (Psychological Software Tools, 2002) script (written by me). The experiment script presented the targets in two sessions to allow for a short break in-between; the targets were randomised only within each session.

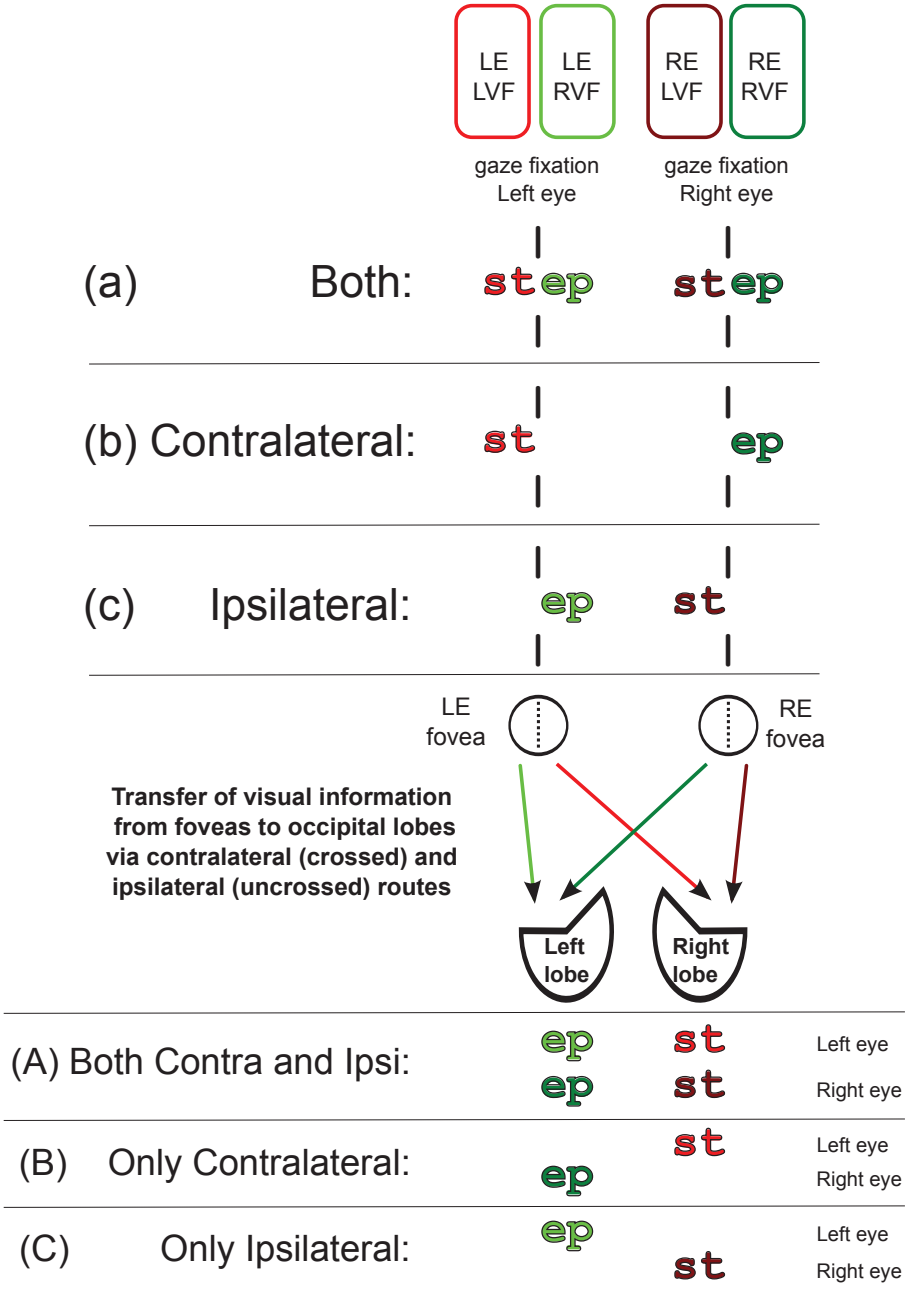


Figure 3.3: Visual hemifoveal field information from each eye is projected to either contralateral or ipsilateral occipital lobes, after each eye has fixated on a previously presented central cue. The three experiment conditions for the target word "step" are portrayed. In the "Both" condition (a), the target is shown completely to both eyes (as in a normal situation in reading with the eyes conjointly fixated) and arrives to the left and right occipital cortices as in (A). With the Contralateral condition (b), the target is divided into left and right half-words and displayed such that the *left* half of the word is presented to the left eye's *left* hemifoveal field (${}^{\mathrm{LE}}LVF_{\mathrm{RH}}$), to the left of a preceding visual cue, while the *right* half-word is shown to the right eye's *right* hemifoveal field (${}_{\mathrm{LH}}RVF^{\mathrm{RE}}$), to the right of a preceding visual cue, with a resulting projection onto the left and right occipital cortices as in (B). For the "Ipsilateral" condition (c), the target word is again shown in two halves, but this time the *left* half-word shown to the right eye's *left* hemifoveal field ($LVF^{\mathrm{RE}}_{\mathrm{RH}}$), to the left of the preceding visual cue, and the *right* half-word is shown to the left eye's *right* hemifield (${}^{\mathrm{LE}}_{\mathrm{LH}}RVF$), to the right of the preceding visual cue, with a resulting projection onto the left and right occipital cortices as in (C).

#### 3.6.1.3 Procedure

I first administered a quick visual test whereby I asked the participant to look through the haploscope, with first one, then the other of the two apertures occluded, and to read aloud the word that was shown in an untimed presentation to both eyes. If they reported seeing the word better or more clearly with one eye than with the other, this was noted[5]. Never-the-less, I did require that participants could clearly read the test word ("word") with each eye independently. I then described the experiment as a perceptual recognition task in which letter strings would appear for a brief period of time. They were not told how long the strings were, nor whether the strings were all words (if they asked before the experiment started, I avoided the question by saying that they would be informed at the end of the experiment). They were then told that their task was to name the word if they saw a word, or name any letters they could discern if they only saw letters. If there was any ambiguity in the spelling of the reported word during the experiment, I asked the participant to name the letters they had perceived.

Table 3.1: Table for selecting target presentation duration for main part of the experiment. Twenty four trials were initially scored for completely correct responses and then used as a lookup into the table below to choose the fastest target presentation duration possible. Responses were matched first against the 14 ms target duration; if they did not match all the 14 ms required correct responses, the 28 ms target duration table was tested. If these id not match, a target duration of 57 ms was used.

| Pretrial duration | Both | Contralateral | Ipsilateral | Target duration |
|---|---|---|---|---|
| 28 | 2,3,4 | 1,2,3,4 | 1,2,3,4 | 14 |
| 57 | 3,4 | 2,3,4 | 2,3,4 | |

| Pretrial duration | Both | Contralateral | Ipsilateral | Target duration |
|---|---|---|---|---|
| 28 | 2,3,4 | 1,2,3 | 1,2,3 | 28 |
| 57 | 2,3,4 | 1,2,3,4 | 1,2,3,4 | |

The first part of the experiment consisted of a procedure to determine the participant's optimal presentation duration for the subsequent main component of the experiment. That is, to find a stimulus presentation duration whereby they gave both erroneous and correct responses in identifying Contralateral and Ipsilateral targets. This pretest consisted of 24 four-letter words (in the same order for all participants) in the three experiment conditions (Both, Contralateral and Ipsilateral) and at two presentation durations (28 and 57 ms). I used correct word identification counts under these six conditions to select an appropriate stimulus duration for the experiment. I used a table

[5] I used this response –$EyesEven$– to see if a lack of vision in one eye could explain any of the variance, or if it associated with the result for my experimental manipulation.

of correct number of responses in each of these six conditions to objectively select an optimal stimulus duration from one of three possibilities: 14, 28 or 57 ms (see Table 3.1).[6]

I then initiated the main part of the experiment, wherein the participant was shown a total of 108 four-letter words in one of three experiment conditions at the previously-determined target presentation duration. When the experiment was completed, I administered a slightly modified version of the Edinburgh Handedness questionnaire (Oldfield, 1971) to ascertain both the participant's hand and eye preferences, which were scored as continuous measures as separate hand and eye lateralisation quotients (i.e., $LQ = 100 * (right-left)/(right+left)$).

[6]Most participants could perform in the desired manner with either 14 or 28 ms presentations, so I did not use those people who needed 57 ms presentations.

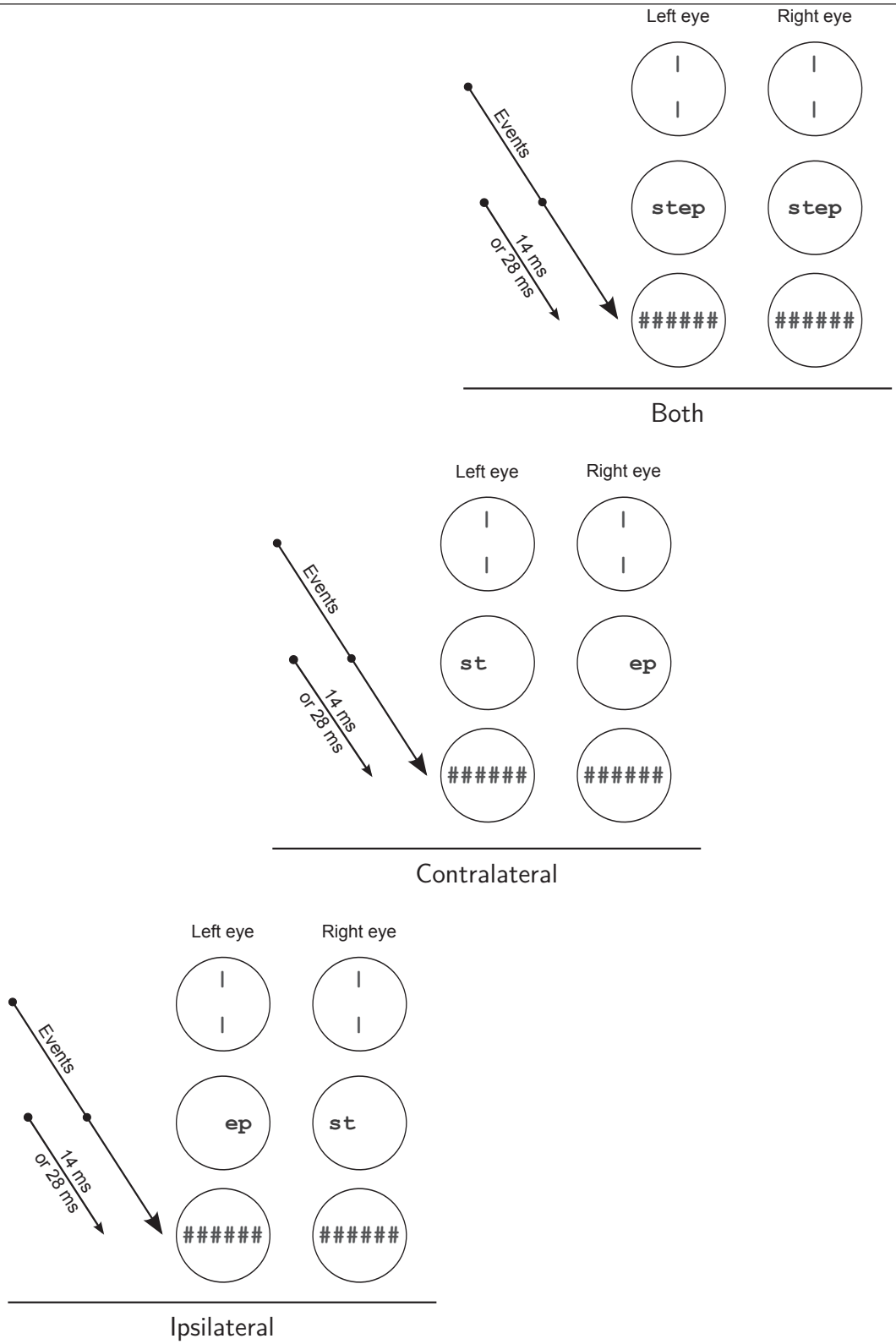


Figure 3.4: Examples of the Both, Contralateral and Ipsilateral experiment condition. The target word is "step" in all three experiment conditions shown. Each case shows what is presented to the left and right eyes, highlighting the fact that the stimuli were only visible for either 14 or 28 ms before a back-mask of hashes appeared. The figures also show the relative positions of the stimuli with respect to the cues for each eye.

**Task description** I asked participants to concentrate their visual attention on the space in the middle of the fixation cue (perceived as a single broken vertical line, even though the same image was shown separately to each eye). I instructed them to bi-manually and simultaneously press two buttons on a button box to start the trial when they felt that they were ready. This is necessary because the two eyes have to be making a stereoscopic (i.e., fused) fixation on the correct space where the stimuli was presented. After a random short delay (between 100 ms and 300 ms) from the bi-manual button press,[7] the two fixation cues were replaced by the two parts of the target stimulus. These stimuli were on the monitor for a very short period before being replaced with a back-mask (see Figure 3.4). I then asked the participant to identify the letter string: to name the word if they felt that they had seen a word, or identify as many letters as possible. I did not record their delay from the onset of the target to their starting to respond as this was an untimed experiment. I typed in their response, after which the visual cues would then appear to both eyes for the start of the next trial.

### 3.6.2 Variables and data analysis

Within-subjects measures consisted of: word frequency, experiment condition and a possible fatigue or practise effect between the first and second halves of the experiment. The between-subjects measures consisted of: $Sex$, $Age$,[8] $MsDur$ (that is, target presentation duration), handedness quotient (from a 10-point questionnaire), and Latin-Square group. I determined eye preference from two questions: $TeleEye$, which eye they used to look into a telescope or keyhole; and $CardEye$, a question I devised whereby I asked participants to look at a card on the other side of the room, then block it out from view with both hands, and finally move their head to look at the card again; I noted whether they moved their head to the left or right to so as look round their hands at the card (a version of the hole-in-the-card test).

Since my experiment depends on participants using both eyes, I encoded another variable, $EyesEven$ {`L<R`, `even`, `L>R`}, referring to the question I asked at the very start of the experiment. The participant saw the same word in full and in an untimed manner with both eyes, and I asked the participant to report what they saw while I first blocked one eye and then the other. If they said that one eye was more clear than the other, I noted this as `L<R` or `L>R`; if they felt that they saw equally well with both eyes, I noted this as `even`. I checked the results from my statistical models for possible interactions with this variable (i.e., I added $EyesEven$ to the model and then compared the two models).

[7] I chose to insert this random delay to give the cortex a time to recover from the intense attention paid to fusing the cues and pressing the buttons.

[8] The variables $Sex$ and $Age$ were not controlled for, so I only included them in exploratory analyses.

The independent measures all made linearly separable contributions to the degree of correctness of the named target; hence I modelled the results with a linear equation and either a binomial distribution (i.e., probability of an exactly correct response), or a Poisson distribution (i.e., number of correct letters in the correct order) for the dependent measure. My analysis of the data treated participant variability and stimuli identity as random factors (Baayen et al., 2008b), contrasting experiment conditions against each other as fixed effects. I added other variables into the linear model if they accounted for a significant amount of variability (as evidenced by an ANOVA comparison between models).

The experimental information was stored in a table that contained the data for all participants, with the scoring of the dependent variable, $Correct$, carried out in batch by a program I wrote in the AWK scripting language. This script first matched each response with its target word to extract which letters were correctly identified, and counted the number of correct letters that were in the correct positions relative to the target (from 0 to 4). For correct/incorrect binomial models, I simply used the relation $(Correct == 4)$ to determine an exact match between target and response.

I also calculated additional variables: $NextPressDelay$, referring to amount of time taken by participants to press the two "ready" buttons to initiate the stimulus presentation of the next trial (that is, the delay from the onset of the fixation cues to the bi-manual pressing of the "I-am-ready" buttons); and $prevCorrect$, the correctness score of the previous trial. For responses that were not exactly correct, I also coded: $CorrectLetters$, the letter positions that were correctly identified, and $L[1,2,3,4]Correct$, whether each letter in positions 1, 2, 3 or 4 were correctly identified, respectively; $Hemisphere$, which cerebral hemisphere was involved in reporting more correct letters from the target; and $Eye$, which eye saw more correct letters from the target.

Furthermore, my AWK script took special care in coding partial responses when the target word had double letters, making sure that only unambiguous letters were used in the scoring. It also noted when a participant had inverted two letters.

I subsequently analysed the data with the $\mathrm{R}$ statistical programming package on a Linux platform. In particular, I used the *LanguageR* and *LME4* libraries (Baayen, 2009; Bates and Maechler, 2009) to carry out Linear Mixed Effects Regression (LMER) analyses to test the influence of my variables on the predictability of correctness of responses. These models use Restricted Maximum Likelihood (REML) estimations for the coefficient means and variance, and are robust to cell-count and variance differences between group levels. Numerical covariates (like $\log(Frequency)$ were recentred around zero in the models, hence the intercept condition uses the mean value of the covariate in its estimation.

In a theoretically-driven manner, initially used both $target$ and $participant$ random effects with the LMER models to see if they explained a significant amount of variance around an intercept-only model. If they did not account for a significant amount of variance (tested by comparing models *with* the added term and models *without* the added term with the $\mathrm{anova}()$ function), I removed then non-significant term from the model. I then added fixed effects terms to the model and again tested for a significant explanation of the overall variance by comparing *with* and *without* models with the $\mathrm{anova}()$ function. I also tested for interactions of each new fixed effect terms other terms in the model to see if there were interaction effects. Again, I compared models *with* the interactions terms against models *without* interaction terms with the $\mathrm{anova}()$ function.

After arriving at the model that significantly explained the overall variance using the variables I was testing for (as fixed effects), I tested whether adding $NextPressDelay$ as a participant random intercept[9] would improve the overall model fit. I also tried adding the fixed effects formula to the random slopes, but removed these if they did not make a significant change to the overall model. In most cases I found that only $NextPressDelay$ (added as a random slope) would make a significant contribution to the overall fit of the model.

I also explored models for possible non-linear effects for the fixed terms by adding them first as exponents ($\exp()$) and then as polynomials ($\mathrm{poly}(..,degree)$). If the new model better explained the overall variance, I used the non-linear terms in the models. I also re-centred numerical terms (with the $\mathrm{scale}(...,scale = F)$), and tested if $\log()$ or $\sqrt{}$ transforms improved model residuals in having better fitting distributions.

I looked at the model covariant matrices (printed below the models with the $\mathrm{summary}()$ function) to see if any terms were covariant. If so, I tested if the model residuals of one term by the other produced a better overall fit for the original model than the separate and possibly co-varying terms. As it turned out, most of my LMER models turned out to have very straightforward fixed effects and random effects formulas.

### 3.6.3 Results

Out of 42 participants, one person reported seeing two sets of cues and therefore was not tested further. Of the remaining participants, only 28 satisfied my requirements for being included in this study. Table 3.2 shows the counts of those participants excluded because they did not satisfy all of my criteria.

With regard to utrocular discrimination (the ability to discern which eye was being stimulated with a specific stimulus), none the of participants reported seeing any of the

[9] During debriefing after the experiment, many participants said that they felt that they had found some trials easier than others. I also found that $NextPressDelay$ durations correlated inversely with correct responses.

letters in one eye but not the other. Furthermore, during debriefing after the experiment, none of the participants were aware that there were presented with different letter strings to each eye.

Interestingly, my first call for participants did not specifically request "native English speakers" (just "fluent English speakers"); I found that non-balanced bilingual but never-the-less fluent English speakers (i.e., those who have grown up in a country where English is not the major –or only– language) were generally poor at identifying even the targets presented completely to both eyes (the Both condition) at the short presentation durations.[10] Consequently, I modified the requirements for my experiment to explicitly request only "native English speakers" and I did not use data from the first group of participants who were not native English speakers.

Table 3.2: Participants who were excluded from the Both/Contralateral/Ipsilateral four-letter words experiment. One other participant could not resolve the two cues into a single image and was not tested further.

| | Excluded |
|---|---|
| Needed too much time to identify stimuli | 2 |
| Non-English | 5 |
| Obtained too few correct for Contra, Ipsi, conditions | 2 |
| Obtained too few correct in Both condition | 4 |

Of those participants that managed to identify stimuli at 14 or 28 ms durations, 27 were right-handed, 1 was left-handed; 21 were female and 7 were male (see Table 3.3). Since there were not enough counts of left-handed participants, I did not use handedness information in the following analyses.

Table 3.3: Numbers of participants by sex and stimulus presentation durations.

| | 14 ms | 28 ms |
|---|---|---|
| Female | 11 | 10 |
| Male | 3 | 4 |

#### 3.6.3.1 Overall results

In terms of percent correct responses for the three experiment conditions, Table 3.4 highlights how the Both condition is most correctly identified by far. As the participants showed a wide range of performance in being able to perceive the intended target, a means-per-participant analysis is not appropriate, hence for the overall results I tally

[10] Apparently, the lack of deep immersion in an English language environment from an early age impacts on our ability to recognise text quickly.

counts of correctness for the experiment conditions over all participants and show these values as percentages.

I found that there were more correct responses under the Contralateral condition than under the Ipsilateral condition. Namely, this results can be summarised by: $Both \gg Contralateral > Ipsilateral$. Furthermore, this pattern of results also holds for both Males and Females (Table 3.5), and for different stimuli presentation durations (Table 3.6). In sections 3.6.3.3 (exactly correct responses) and 3.6.3.7 (partially correct responses) I will explore the statistical validity of these findings.

Table 3.4: Percent of exactly correct responses by experiment condition. In terms of exactly correct responses, the result is: $Both \gg Contralateral > Ipsilateral$.

| N | Both | Contralateral | Ipsilateral |
|---|---|---|---|
| 28.0 | 91.3 | 65.3 | 60.5 |

Table 3.5: Percent correct responses, sex by experiment condition. Number of participants is shown in column "N".

| | N | Both | Contralateral | Ipsilateral |
|---|---|---|---|---|
| Female | 21.0 | 91.0 | 63.2 | 59.9 |
| Male | 7.0 | 92.1 | 71.4 | 62.3 |

Table 3.6: Percent correct responses, target presentation duration by experiment condition.

| | N | Both | Contralateral | Ipsilateral |
|---|---|---|---|---|
| 14ms | 14.0 | 88.3 | 59.3 | 52.2 |
| 28ms | 14.0 | 94.2 | 71.2 | 68.8 |

Regarding my simple bi-ocular pre-test evaluation, I found that a difference in acuity between left and right eyes did not make a difference in people's ability to carry out this experiment (Table 3.7). Interestingly, there was only one participant who reported that their right eye was better than their left eye, and this Female happened to correctly identify more ipsilaterally presented stimuli than contralaterally presented stimuli. I will examine the issue of Sex and Lateralisation in Chapter 5 where I explicitly control for Sex. My results in Chapter 5 suggest that this finding here is plausible.

Most psychological experiments that use visual information simply require "normal or corrected-to-normal" vision; however since contact lenses usually do not correct for asphericity, I looked at how participants with different types of "corrected-to-normal"

Table 3.7: Percent correct responses, bi-ocular pretest by experiment condition.

| | N | Both | Contralateral | Ipsilateral |
|---|---|---|---|---|
| L > R | 5.0 | 88.3 | 66.7 | 52.8 |
| L < R | 1.0 | 100.0 | 66.7 | 75.0 |
| Eyes Even | 22.0 | 91.5 | 64.9 | 61.6 |

vision performed. Table 3.8 shows that participants with contact lenses performed more poorly in the half-word conditions than those with glasses.

Table 3.8: Percent correct responses, vision correction by experiment condition. As before, whereas the Both condition was mostly correctly perceived, those with contact lenses performed more poorly when their eyes were shown only half the target word (the Contralateral and Ipsilateral conditions).

| | N | Both | Contralateral | Ipsilateral |
|---|---|---|---|---|
| Contact lenses | 4.0 | 91.7 | 44.4 | 41.0 |
| Glasses | 16.0 | 89.4 | 65.5 | 58.7 |
| None | 8.0 | 94.8 | 75.3 | 74.0 |

#### 3.6.3.2 Individual differences

The very nature of this experiment is to challenge participants so that they are likely to make mistakes in perceiving the stimuli. This is accomplished by using very short presentation durations followed by a back-mask. Hence, I compare performances on the three experiment conditions by contrasting the probability of getting each condition correct (a within-subject's comparison). I found that there was a lot of variation in the performances of participants, with some able to perceive stimuli with only 14 ms presentation durations whereas others needed 28 ms. Furthermore, whereas most managed to correctly identify 32 or more (out of 36) of the Both condition stimuli, there was a lot of variability in being able to correctly identify all four letters in the Contralateral and Ipsilateral conditions (see Figure 3.5), ranging from some participants who only managed to correctly identify around five Contralaterally or Ipsilaterally presented targets, to others who managed to ascertain 30 Contralateral or Ipsilateral conditions.

The large differences between participants does not affect my analyses since, I carried out the statistics as within-subjects comparisons between conditions. To accomplish this, I used Linear Mixed Effects Regression models with participants as target as random effects.[11]

[11]See Baayen et al. (2008b), for a more complete treatment of participant random effects in psycholinguistic experiments

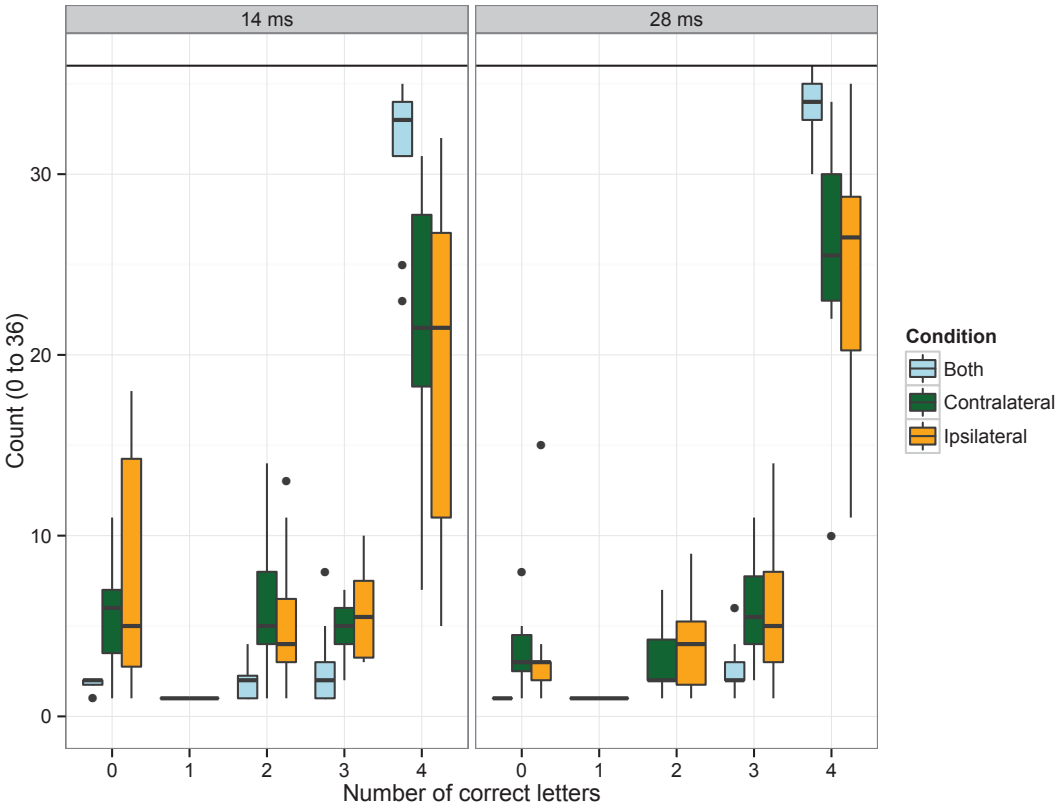


Figure 3.5: Number of responses per person for Both, Contralateral and Ipsilateral experiment conditions, per number of correctly identified letters. Whereas most participants managed to identify all four letters in targets presented in the Both condition, there was a wide range of performance between participants on the Contralateral and Ipsilateral conditions.

#### 3.6.3.3 Modelling correct responses

As each response was said aloud by the participant, I typed it in to the computer (I asked the participant to name the letters if there was any confusion regarding the spelling of the response). Hence, the data I collected contains all the responses, including both correct and incorrect utterances.

A first question is: how capable were participants of correctly identifying the 108 stimuli (36 Both, 36 Contralateral and 36 Ipsilateral)? I explored the probability of correct responses under different conditions with binomial LMER models, with item and participant random effects. I will present my analyses as a process of building up the regression model by successively including independent predictors and testing the augmented model against the previous model with an ANOVA comparison to objectively determine whether the new model is both parsimonious and significantly explains more of the variance.

**Participant confidence in correctness of responses** Since this experiment requires participants to make a *conjoint* fixation on the vertical cue lines before the stimulus is shown, I designed the task to be initiated by the participant when they felt that they "were clearly and easily focusing on the space between the two vertical cue lines". They started the onset of the next stimulus by bimanually pressing two buttons on a button box when they were ready. I noticed that participants seemed to be pressing the buttons quickly to start the following trial after they had straightforwardly identified the previous target, and they seemed to take longer in starting the next trial when they were unsure what the previous target was. Consequently, I used this delay in initiating the next trial ($\mathbf{NextPressDelay}$) as an intercept per participant for the current trial; I propose that it could be a measure of confidence in the participant's performance on the current trial. The outcome of including this measure as an per-participant intercept is that these LMER models better explain the overall variance, as evidenced by smaller deviance measures for Model 3.2 than for Model 3.1. The model equations are shown in Figure 3.6, and the ANOVA comparison between the two models is shown in Table 3.9. Here we see that the values for the AIC (Akaike Information Criterion), BIC (Bayesian Information Criterion), and logLik (log Likelihood) model parameters are smaller for Model 3.2 and the two models are significantly different $\left(\chi^2_{(df=2)} = 164.79, p < 0.001\right)$. The ANOVA function uses $\chi^2$ comparisons between these models due to the non-normal binomial dependant measure, $\mathbf{Correct} = 4$.

$$\begin{aligned} Correct\{\text{no},\text{yes}\} \;\sim\; & \log(Frequency) + \\ & (1 \mid Participant) + (1 \mid Target), \\ & \text{model} \;=\; \text{binomial} \end{aligned} \tag{3.1}$$

$$\begin{aligned} Correct\{\text{no},\text{yes}\} \;\sim\; & \log(Frequency) + \\ & (\sqrt{NextPressDelay} \mid Participant) + (1 \mid Target), \\ & \text{model} \;=\; \text{binomial} \end{aligned} \tag{3.2}$$

Figure 3.6: Model equations for the base explainability of correct response by target frequency, without (Model 3.1) and with $\mathbf{NextPressDelay}$ (Model 3.2) used as a per-participant intercept.

**Notation for writing models** I will use a writing notation very similar to the actual formula used in $\mathrm{R}$ to represent the LMER models, with the dependant variable on the left of the model equation sign, '$\sim$'. The linear independent measures are then listed on the right of the '$\sim$', with a '$+$' to indicate that the term is included without any interactions, and a '$*$' to mean that the two flanking terms will also include the interaction term

(written on the plots and in the tables as, "$termA : termB$"). When a measure is categorical, I list the possible levels within '{}', with the first level being included into the calculation of the model intercept. Following the independent variables, I list the mini-models for random effects as '$(intercept|randomMeasure)$'. I then identify how the error term for the dependant measure is modelled; possible options are: binomial, poisson or gaussian. If the data used is a specific subset, I include a line stating how the data was *subset()* from the R data frame.

Table 3.9: ANOVA comparison between Models 3.1 and 3.2, showing that the **NextPressDelay** random intercept per participant provides significantly more explainability to Model 3.2.

| | Df | AIC | BIC | logLik | Chisq | Chi Df | Pr(>Chisq) |
|---|---|---|---|---|---|---|---|
| Model 3.1: | 4 | 3162.42 | 3186.48 | -1577.21 | | | |
| Model 3.2: | 6 | 3002.37 | 3038.32 | -1495.19 | 164.05 | 2 | *** |

Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

#### 3.6.3.4 Both, Contralateral and Ipsilateral effects on correctness of response

The following step in the analysis is to include my experiment condition in the model, making sure that the parameter contrasts highlight the differences I hypothesise, namely, Contralateral being different from Ipsilateral. I will also include stimulus presentation duration within the analysis, as we see that participants achieved more correct responses with a 28 ms duration than with 14 ms (Table 3.6).

$$\begin{aligned} Correct\{\text{no},\text{yes}\} \sim\ & Condition\{\text{Ipsi},\text{Both},\text{Contra}\} + \log(Frequency) + \\ & (\sqrt{NextPressDelay} \mid Participant) + (1 \mid Target), \\ & \text{model} = \text{binomial} \end{aligned} \tag{3.3}$$

$$\begin{aligned} Correct\{\text{no},\text{yes}\} \sim\ & Condition\{\text{Ipsi},\text{Both},\text{Contra}\} + \\ & StimDuration\{14\text{ms}, 28\text{ms}\} + \log(Frequency) + \\ & (\sqrt{NextPressDelay} \mid Participant) + (1 \mid Target), \\ & \text{model} = \text{binomial} \end{aligned} \tag{3.4}$$

Figure 3.7: Model equations including experiment condition (Model 3.3) and stimuli presentation duration (Model 3.4), with the Ipsilateral case as part of the intercept and therefore comparable to the Contralateral and Both cases.

Figure 3.7 shows the model equations (Models 3.3 and 3.4, with stimulation presentation duration included); the graphs in Figures 3.8 and 3.9 depict each of the fixed

predictor coefficients contrasted with the intercept case for Models 3.3 and 3.4, respectively.

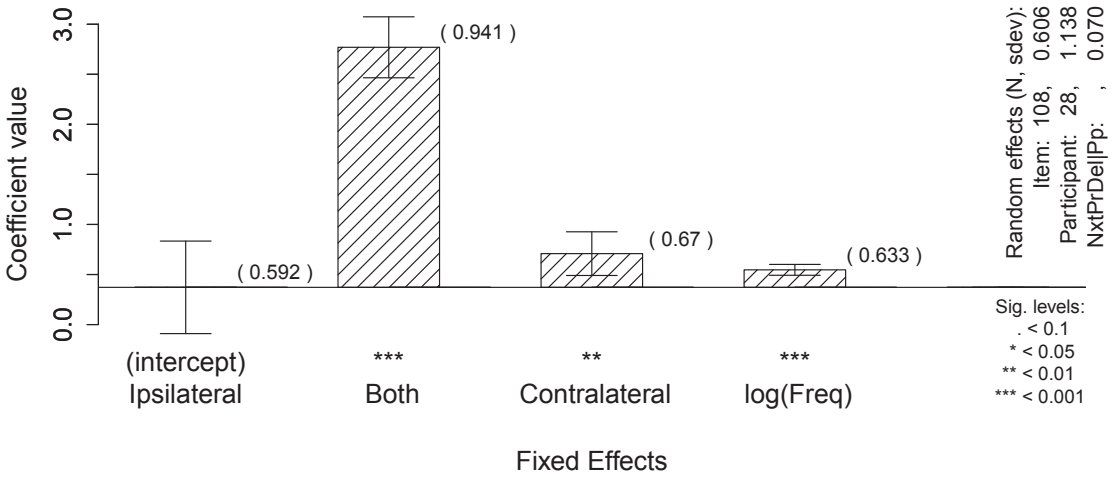


Figure 3.8: The LMER model for probability of correct word identifications (Model 3.3), with the Both and Contralateral experiment conditions compared to the Ipsilateral condition. The first bar represents the intercept case and is thus the value against which the other bars are compared to. The following bars represent the main effects terms and represent how their value differs from the intercept case, and can be either greater or less than the value of the intercept coefficient. The vertical axis corresponds to the $\beta$ coefficients for the bars. 95% confidence intervals are extracted from the Z-score analysis and are shown as whisker lines for each of the terms. Probability of correctness estimations for each term are shown in parenthesis next to each bar. The random effects count and standard deviance values are written vertically to the right.

While Model 3.4 better explains the overall variance ($p < 0.05$, Table 3.10), the addition of stimulus presentation duration does not modify the effects of experiment condition in Model 3.3. Furthermore, there is no interaction between experiment condition and stimulus presentation duration (ANOVA comparisons between models is not significant, analysis not shown). Consequently, I will use Model 3.3 as the more parsimonious model to interpret the effects of experiment condition.

As expected, the word frequency covariate contributed significantly to correctness of response; however its slope was small in comparison to the other factors (word frequency: $\beta\, slope = 0.17,\ Z = 6.5,\ p < 0.001$; see Table 3.11). On the other hand, having the full stimulus presented simultaneously to both eyes greatly facilitated a correct response relative to an Ipsilateral presentation (Both: $\beta\, slope = 2.4,\ Z = 15.8,\ p < 0.001$. Most interestingly, a Contralateral presentation of stimuli had a probability of correctness of response that is different from an Ipsilateral presentation. Contralateral presentations were 8.5% more likely to be correctly perceived than Ipsilateral presentations (found by

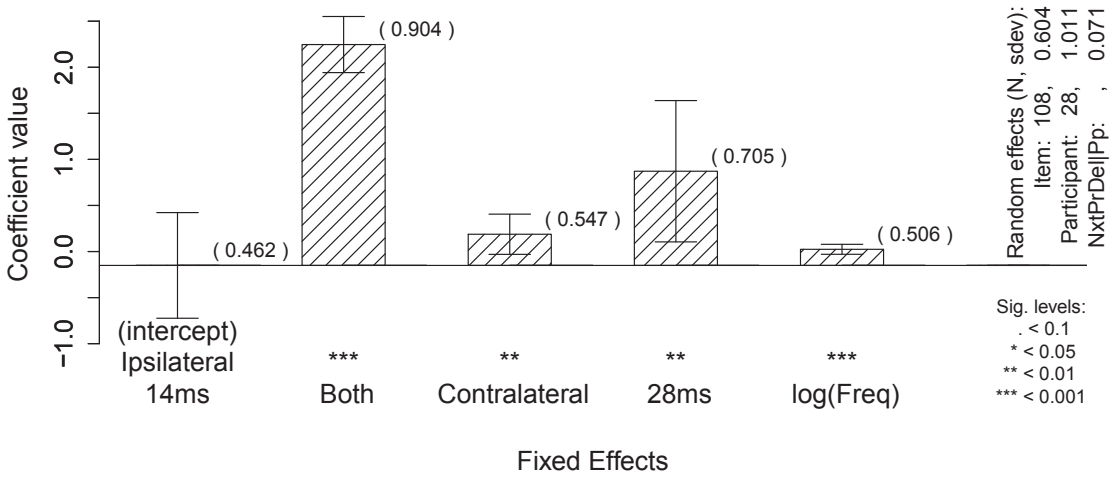


Figure 3.9: Plot of the LMER model (Model 3.4) for probability of correct word identifications, with 28 ms stimuli presentation duration compared to the 14 ms case (included with the intercept), and the Both and Contralateral experiment conditions compared to the Ipsilateral condition. This model finds that the more time the stimuli is shown for, the more likely participants are to correctly identify the target, however, with grater variability and hence the 28 ms is not so significantly different $(p < 0.05)$ from the 14 ms case. Moreover, the comparison between Contralateral and Ipsilateral experiment conditions holds: the Contralateral case is 8.5% more likely to be correctly identified than the Ipsilateral case, with $p < 0.01$.

Table 3.10: ANOVA comparison between Models 3.3 and 3.4, showing that the addition of stimuli presentation duration to the model explains a further significant portion of the variance over Model 3.3. However, the main findings of the differences in experiment conditions are not changed from Model 3.3, as determined by comparing Figures 3.8 and 3.9.

| | Df | AIC | BIC | logLik | Chisq | Chi Df | Pr(>Chisq) |
|---|---|---|---|---|---|---|---|
| Model 3.3: | 8 | 2665.81 | 2713.74 | -1324.90 | | | |
| Model 3.4: | 9 | 2661.56 | 2715.48 | -1321.78 | 6.25 | 1 | * |

Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

comparing probability estimates shown in parenthesis next to the relevant bars for each factor in Figure 3.8). Specifically, the Contralateral condition had a positive $slope = 0.34$ ($Z = 3.09$, $p < 0.01$, Table 3.11) over the Ipsilateral condition.

#### 3.6.3.5 The effect of presentation duration on Sex and laterality of presentation

There is a question regarding sex differences in lateralisation visual stimuli (see, for example, Zaroff, Knutelska, and Frumkes, 2003). Although Sex was not controlled for in this experiment, there were several participants in the Sex versus Presentation

Table 3.11: Contribution of the fixed effects to the probability of correct responses for model 3.3. As can be seen, the Contralateral experiment condition has a significantly larger coefficient value by $\beta = 0.34$ ($p < 0.01$) than the Ipsilateral experiment condition (included in the intercept case).

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Ipsilateral | 0.3718 | 0.3718 | 0.2310 | 1.6092 | |
| 1 | Both | 2.7693 | 2.3975 | 0.1522 | 15.7530 | *** |
| 2 | Contralateral | 0.7085 | 0.3367 | 0.1091 | 3.0870 | ** |
| 3 | log(Frequency) | 0.5467 | 0.1749 | 0.0271 | 6.4541 | *** |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Target | 108 | 0.3669 | 0.6057 |
| Participant | 28 | 1.2961 | 1.1385 |
| NxtPrDel\|Pp | | 0.0048 | 0.0696 |

Duration cells (Table 3.3). A plot of Accuracy probability shows a possible interaction (Figure 3.10): whereas Males are more likely to ascertain the Contralateral trials at either of the two presentation durations, Females show an apparent interaction where Ipsilateral trials are more poorly identified at shorter durations but better identified at longer durations.

I modelled this data and found that indeed these effects are statistically significant (Table 3.12).

#### 3.6.3.6 Other independent factors

Other factors like experiment session or Latin Square design did not contribute significantly to correctness of response (analyses not shown). $Age$, $Handedness$ and ocular preference were not explicitly controlled for in the participant pool; a post-hoc analysis showed that there were too few counts of Left-handed or Left-eyed participants to include these measures in further analyses. Finally, $Age$ did not significantly explain any of the variance in Model 3.3, neither did it have an interaction effect with experiment condition.

#### 3.6.3.7 Analysis of partially correct responses

Sometimes participants did not manage to correctly perceive the target but did report several letters. My AWK script identified which letters were correctly named by matching letters from participant responses to targets and counting the number of correctly named letters. There were in total 613 erroneous responses where participants recognised at least two letters correctly from the target.

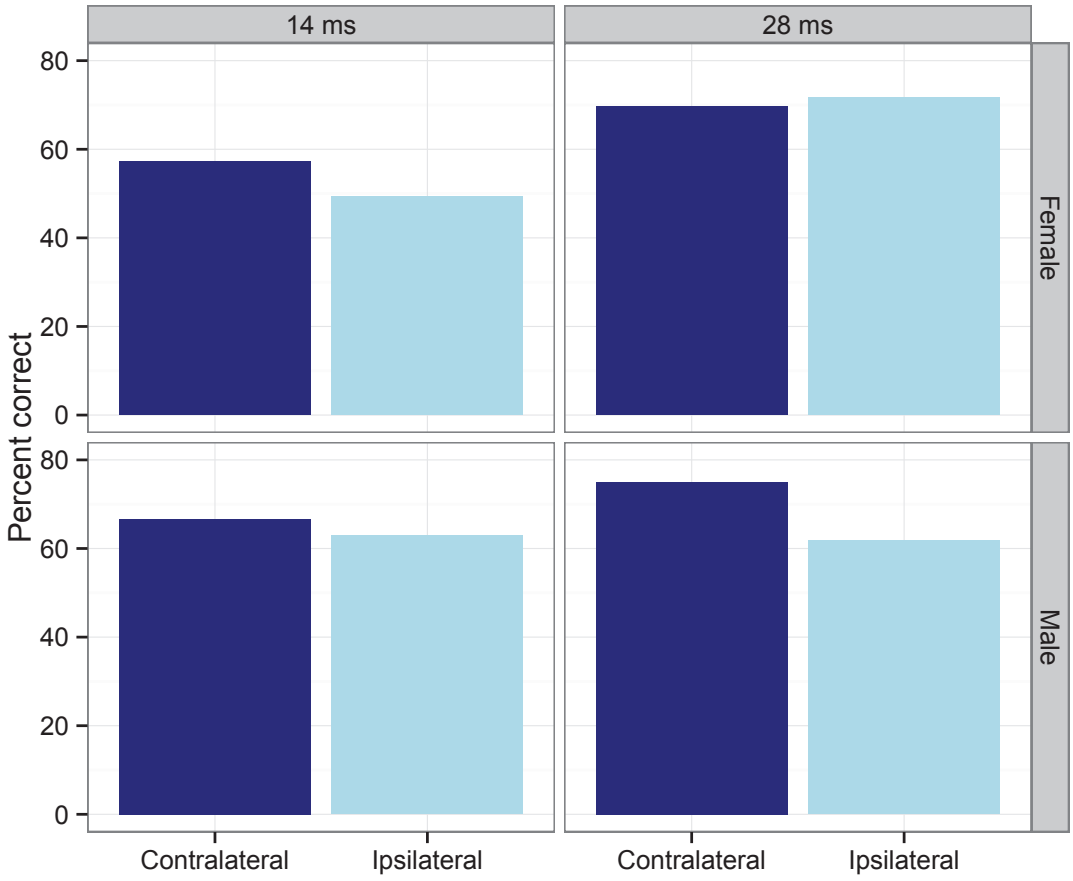


Figure 3.10: Probability of correct responses are plotted for the Contralateral and Ipsilateral experiment conditions, for Females and Males who undertook the experiment at either 14 or 28 ms stimuli presentation durations. As can be seen, whereas Males are more likely to ascertain the Contralateral trials at either of the two presentation durations, Females show an apparent interaction where Ipsilateral trials are more poorly identified at shorter durations but better identified at longer durations.

Overall, no letter position was any more correctly identified than any other in these partial responses (counts per letter position: $L1 = 422, L2 = 417, L3 = 352, L4 = 393$, $\chi^2_{df=3} = 7.73, ns$). Furthermore, grouping by patterns of correctly identified letters shows that there were a lot of "near misses", where participants named 3 out of the 4 letters correctly (the bars labelled "123_", "_234", "12_4" and "1_34" in Figure 3.11; and even all four correct but with flanking extra letters named, labelled "1234"). However, none of these 3-letter "near miss"cases was significantly more produced than any other. Consequently, I will only address the large asymmetry in begin- and end-bigram responses.

**When only the left or right bigram is identified** Participants correctly identified the beginning bigram ("12___", projected to the RH, count=98) more often than the

Table 3.12: LMER model for probability of correct responses, highlighting the interaction between Sex and stimuli presentation duration, between Contralateral and Ipsilateral experiment conditions.

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Female;Contra;14ms | -0.0596 | -0.0596 | 0.3448 | -0.1727 | |
| 1 | Male | 0.7361 | 0.7956 | 0.7533 | 1.0562 | (ns) |
| 2 | Ipsilateral | -0.6454 | -0.5859 | 0.1736 | -3.3755 | *** |
| 3 | 28ms | 0.8594 | 0.9190 | 0.4841 | 1.8983 | (.) |
| 4 | log(Frequency) | 0.1301 | 0.1897 | 0.0289 | 6.5682 | *** |
| 5 | Male:Ipsi | 0.5214 | 0.3713 | 0.3754 | 0.9890 | (ns) |
| 6 | Male:28ms | 1.4100 | -0.2450 | 0.9971 | -0.2457 | (ns) |
| 7 | Ipsi:28ms | 0.9389 | 0.6654 | 0.2612 | 2.5477 | * |
| 8 | Male:Ipsi:28ms | -0.1899 | -1.2591 | 0.5105 | -2.4665 | * |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Target | 108 | 0.3921 | 0.6262 |
| Participant | 28 | 1.2647 | 1.1246 |
| NxtPrDel\|Pp | | 0.0055 | 0.0741 |

ending bigram ("__34", projected to the LH, count=$52$; see Figure 3.11). Although there were not enough counts of Males for a statistically valid comparison, Males seem to have a different pattern of Hemispheric responses from Females (Fig. 3.12). That is, whereas Females produce relatively more RH bigram identifications in the Ipsilateral case than in the Contralateral case, Males produce more RH bigram identifications in the Contralateral case than in the Ipsilateral case.

**A model for partially correct responses** By storing the partially correct responses (at least two letters correctly named from the target) and assigning an count of correct letters to each utterance, I could then explore the relationships between the independent measures and probability of correctness. This would highlight what variables impinge on visual perception. I followed the same methodology as before: constructing a parsimonious LMER model by means of ANOVA comparisons between models which successively included the different independent measures and interactions; I will only show my analysis for the final model from this process (Model 3.5). Sex, eye-evenness, visual correction apparatus, eye preference, handedness, and word frequency were not significant contributors to partial correctness. I left the non-significant and almost-zero slope $\log(Frequency)$ term in the model to show that there was no recognition of the

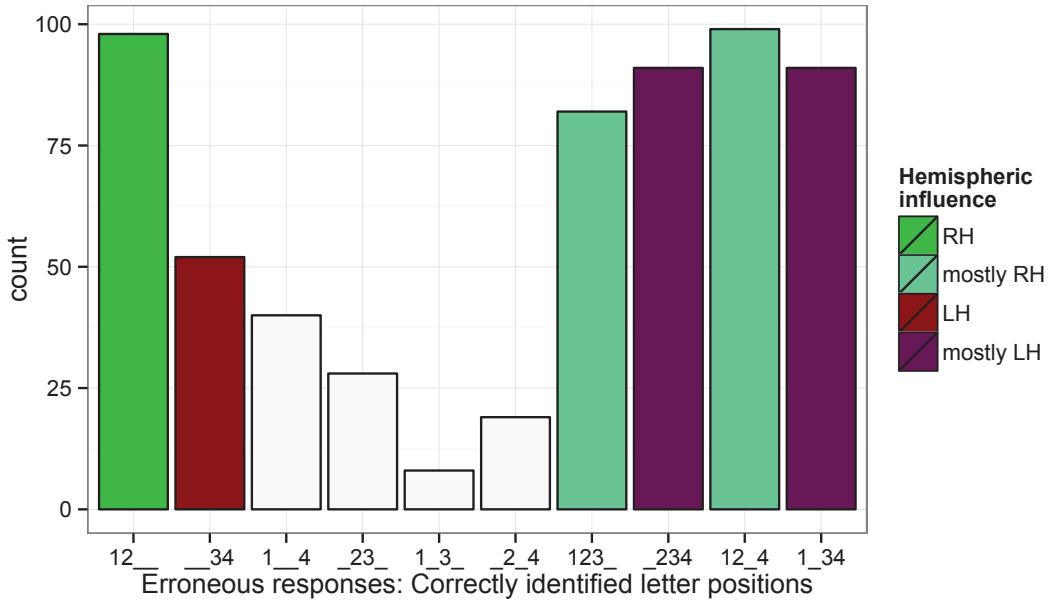


Figure 3.11: Partially correct perceptions: Groups of correctly identified letters in erroneous responses. Letter positions 1 and 2 are always shown to LVF, but either to the LE $({}^{\mathrm{LE}}LVF_{\mathrm{RH}})$ or to the RE $(LVF^{\mathrm{RE}}_{\mathrm{RH}})$ or both eyes LVF, depending on experiment condition (*Contralateral*, *Ipsilateral* or *Both*, respectively). Similarly, letter positions 3 and 4 are always shown to RVF and shown to either RE $({}_{\mathrm{LH}}RVF^{\mathrm{RE}})$, LE $({}^{\mathrm{LE}}_{\mathrm{LH}}RVF)$ or both eyes RVF, depending on experiment condition. An "_" means that the letter in that position was not correctly named, or missed altogether. Note that there were a few responses where all letters were correctly identified, but the participant named more than 4 letters (that is, they named flanking letters to the target, labelled "1234"), and were not counted as correct responses.

target word (see Table 3.14). That is, this model rules out the possible situation where participants recognised the target but tended to make errors in reporting the letters.

Only experiment condition, stimulus presentation duration and hemispheric influence mattered for modelling partially correct responses (i.e, explained a significant portion of the variance in the LMER model). For the latter measure, hemispheric influence was determined by the correctly named letter positions in erroneous responses (see Table 3.13). The rational I used in constructing this coding scheme was that of "majority of letters from a visual field", independent of experiment condition. If there were more letters identified from one half than from the other half of the target, I coded this to be an influence from the side with the more correctly identified letters; if there were even numbers of letters identified from both sides of the target, I coded this as a "Both hemispheres" influence.

The LMER model for partially correct responses is shown in Figure 3.13. I found that the interaction between stimulus presentation duration and experiment condition

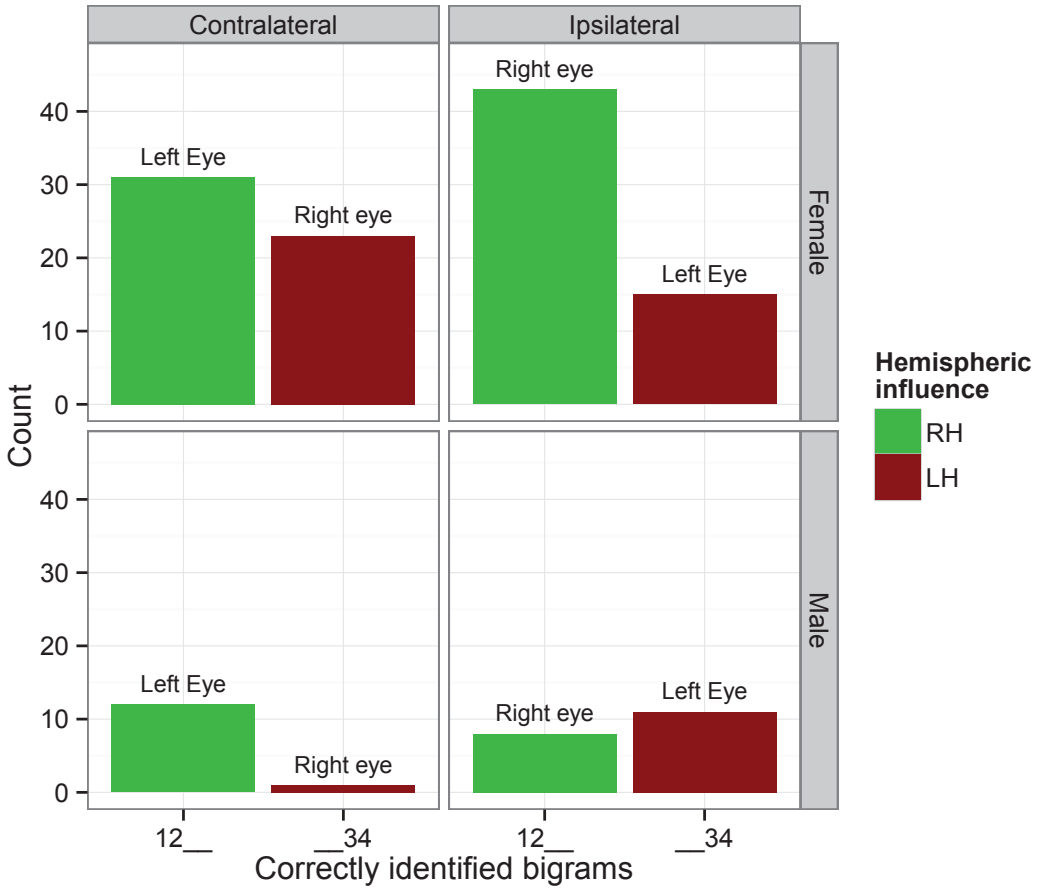


Figure 3.12: Proportions of correctly identified bigrams for Left Eye (LE) and Right Eye (RE), for sex and for experiment condition. Only the Contralateral and Ipsilateral experiment conditions are shown as it is only in these conditions that the bigrams were shown exclusively to one eye or the other eye. The Begin bigrams ("12___") were projected to the Right Hemisphere (RH, shown in green or light grey), and the End bigrams were projected to the Left Hemisphere (LH, shown in red or dark grey).

was significant, so I show this in the model equation by means of an "*" between the two independent measures. Since the linear regression models in **R** assume "treatment contrasts" by default, the value of the interaction in the analysis represents a measure of how different the interaction term is from the expected value resulting from solely the main effects involved in the interaction. Consequently, I plot both the expected value (light shaded bar) and the overall interaction value (dark shaded bar) so that the interaction effect –the difference between these two bars– is clearly visible (the last two fixed effects terms in Figure 3.14).

While partial correctness for the Contralateral condition was slightly lower than the Ipsilateral condition at 14 ms ($slope = -0.056, p < .05$), there was a strong facilita-

Table 3.13: Classification of hemispheric influence from patterns of correctly identified letters in erroneous responses. A "_" means that the letter in that position was not correctly identified.

| Hemispheric influence | Correctly identified letter positions |
|---|---|
| Both Hemispheres | "1_3_" "1__4" "_23_" "_2_4" "1234"+ |
| Left Hemisphere (from RVF) | "__34" "_234" "1_34" |
| Right Hemisphere (from LVF) | "12__" "123_" "12_4" |

+In this case participants identified all 4 letters correctly, but they also named other (flanking) letters and hence did not exactly identify the target.

$$\begin{aligned} Correct \sim\ & Condition\{\text{Ipsi}, \text{Both}, \text{Contra}\} * StimulusDuration\{14\text{ms}, 28\text{ms}\} + \\ & Hemisphere\{Right, Left\} + \\ & (1 \mid Participant), \\ & \text{model} = \text{poisson}, \\ & \text{data } \{(\text{Hemisphere in RH}, \text{LH})\} \end{aligned} \tag{3.5}$$

Figure 3.13: Model equation for partially correct responses. I built up the model by successively including independent measures and possible interactions that significantly explained overall variance. This process showed that the interaction between experiment condition and stimulus duration was important. Note that the error distribution around $Correct$ is modelled with a Poisson distribution which is appropriate for finite ordinal data.

tion for Contralateral presentation over Ipsilateral presentation at 28 ms ($predict = 2.9$, $slope = 0.146$, $Z = 3.87$, $p < 0.001$; see Table 3.14).

Responses with two or three letters correct, where the end-bigram was completely identified (the "LH" term, predicted correctness score$= 3.2$, $slope = 0.112$, $Z = 6.4$, $p < 0.001$, from Table 3.14) achieved significantly higher correctness scores than two or three correct letter partial responses where the beginning bigram was completely identified (the "RH" term, included in the intercept case, predicted correctness score). That is, there were higher partial-response scores with more letters correct in LH-dominated situations than in RH-dominated situations.

While this result appears to be in contrast to the cases where just one bigram was correctly identified (section 3.6.3.7), where the beginning bigrams (a RH response) were identified more often than the ending bigrams (a LH response), this is due to a confusion in the LH/RH naming convention I am using. In three letter responses, it is the contribution of the *other* hemisphere that makes a difference: Apart from the fully identified bigrams in three-letter partial correct responses, the RH is better at identifying parts of its bigram than the LH is. Hence, the entries I have labelled as "LH" really

Table 3.14: Analysis of partially correct responses for Model 3.5. The intercept case represents the base level for three factors: $(i)$ the Ipsilateral experiment condition ["Ipsi"]; $(ii)$ a 14 ms stimulus presentation duration ["14ms"]; and $(iii)$ an influence from letters in the responses that mostly arrive to the right hemisphere ["RH"]. Compared against this intercept are: the Both ["Both"] and Contralateral ["Contra"] experiment conditions; stimulus presentation duration at 28 ms ["28ms"]; the hemispheric effects from more letters in the responses that arrive to either both hemispheres ["BH"] or the left hemisphere ["LH"]; the $\log(frequency)$ of the target word; and the interaction effects between experiment condition and stimulus presentation duration ["Both:28ms" and "Contra:28ms", respectively]. Note that there is no term labelled "Both:14ms" or "Contra:14ms"; this is because the fixed effect term for the "Both" bar represents the difference between "Ipsi:14ms" (part of the intercept case) and "Both:14ms", namely, the Both experiment condition.

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Ipsi;14ms;RH | 2.5194 | 3.2266 | 0.0406 | 79.4978 | |
| 1 | Both | 2.9992 | 0.1743 | 0.0344 | 5.0636 | *** |
| 2 | Contra | 2.3825 | -0.0559 | 0.0263 | -2.1224 | * |
| 3 | 28ms | 2.4879 | -0.0126 | 0.0575 | -0.2191 | (ns) |
| 4 | LH | 3.1719 | 0.1119 | 0.0175 | 6.3745 | *** |
| 5 | Both:28ms | 2.6576 | 0.0534 | 0.0536 | 0.9958 | (ns) |
| 6 | Contra:28ms | 2.9151 | 0.1459 | 0.0377 | 3.8698 | *** |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Participant | 28 | 0.0177 | 0.1332 |

speak to the advantage of the RH in identifying single letters of its LVF bigram than the LH in identifying single letters of its RVF bigram.

#### 3.6.3.8 Using the comprehensive data set for analysis

The design of my scoring of correctness implies that the higher total score achieved per condition (i.e., sum of all scores per experiment condition, per participant) is a direct consequence of a participant's ability to perform the task in this condition. Hence, I can use the full data (that is, all the trials and their correctness scores from 0 to 4) to model participant performance under each experimental condition. Thus, the overall correctness scores achieved (i.e., the fixed term coefficients in an LMER model) in the Contralateral and Ipsilateral experiment conditions will reflect their ability to perform the experiment in these circumstances, and hence compare performance abilities in these two conditions.

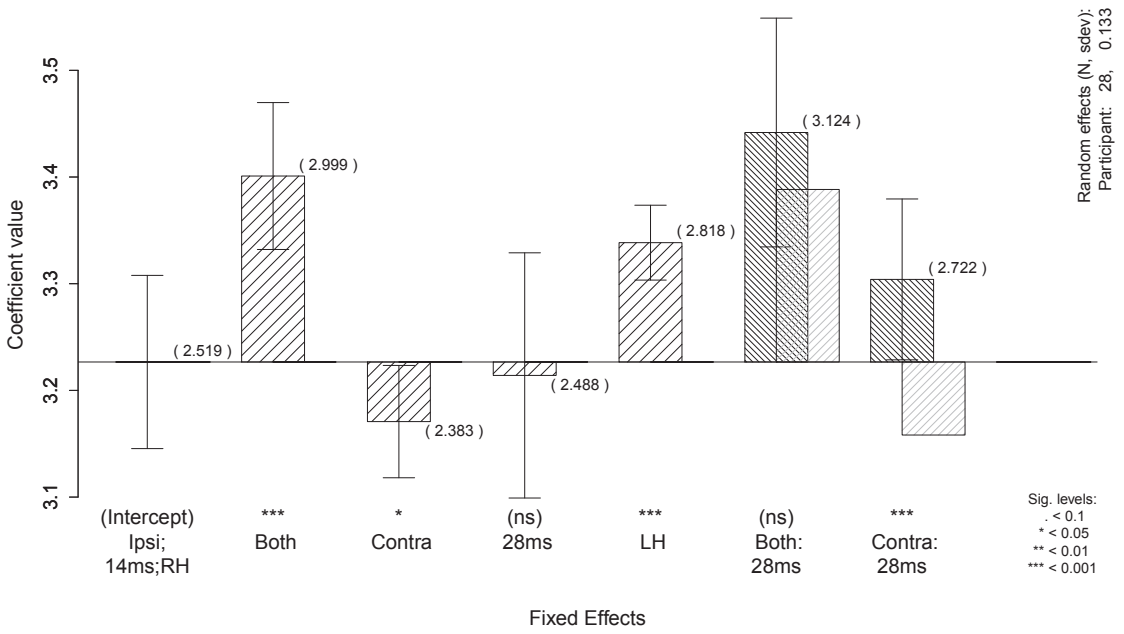


Figure 3.14: Plot of LMER Model 3.5 for partially correct responses. The values for the heights of the bars in parenthesis correspond to the predicted values for $Correctness$. All completely correct responses and responses where no hemisphere could be inferred from the response letters have been excluded, leaving 591 data points for the model. The right two bars show the interaction between stimulus duration and experiment condition. Whereas the light shaded bars show the expected values due to main effects, the dark shaded bars show the full values of the interaction: if these bars are statistically different then there is an interaction effect.

Table 3.15: Mean score for each experiment condition. Results are shown for 14 and 28 ms presentation durations and for Sex.

| N | Duration | Sex | Both | Contralateral | Ipsilateral |
|---|---|---|---|---|---|
| 11 | 14 ms | Female | 3.79 | 3.03 | 2.72 |
| 10 | 28 ms | Female | 3.93 | 3.44 | 3.41 |
| | | | | | |
| 3 | 14 ms | Male | 3.89 | 3.24 | 3.28 |
| 4 | 28 ms | Male | 3.86 | 3.59 | 3.34 |

Table 3.15 shows the mean scores for each experiment condition, aggregated per participant. In most cases, the Contralateral condition has a higher mean score than the Ipsilateral condition.[12] Interestingly, whereas Males appear to perform better than Females, Females show a larger performance difference at 14 ms and Males show a larger performance difference at 28 ms on the Contralateral and Ipsilateral conditions.

[12]I do not show standard deviations for these means as the range of possible values is limited from 0.0 to 4.0 and their distributions are not normal.

To clarify, the largest difference in mean scores for Females occurs for Ipsilateral trails between 14 and 28 ms; whereas for Males the largest difference in mean scores occurs for Contralateral trials between 14 and 28 ms. In other words, while Females do relatively better on Ipsilateral trials at 28 ms, Males do relatively better on Contralateral trials at 28 ms.

$$\begin{aligned} Correct\{0..4\} \quad \sim \quad & Condition\{\text{Ipsi}, \text{Contra}\} * Sex\{Female, Male\} * \\ & StimulusDuration\{14\text{ms}, 28\text{ms}\} + \\ & (\sqrt{NextPressDelay} \mid Participant) + (1 \mid Target), \\ & \text{model} \ = \ \text{poisson}, \\ & \text{Just Contralateral and Ipsilateral cases} \end{aligned} \tag{3.6}$$

Figure 3.15: Model Equation for comprehensive analysis of Contralateral and Ipsilateral cases.

To test this, I ran an LMER model for comparing the Ipsilateral to the Contralateral experiment condition for the comprehensive data. The model design is shown in Fig. 3.15, and the LMER results are plotted in Fig. 3.16. As the interactions terms are significant I show these in the results (plotted as dark grey bars overlapping the light grey bars that represent the expected values for the interaction terms).

The LMER analysis (Fig. 3.16) shows that the differences in means that are observed in Table 3.15 are significant. All comparisons are against the intercept case that represents the correctness score for Ipsilateral conditions presented for 14 ms to Females (correctness score$= 3.36$). Two fixed terms are significant: Contralaterally presented targets elicited a higher correctness score (the Contra coefficient, correctness score$= 3.49$); and a longer presentation duration significantly enhances overall performance (correctness score$= 3.70$). While Males appear to achieve a higher correctness score, they also have varied performances and thus are not significantly different from Females.

The two-way interaction terms show important traits: Contralaterally presented stimuli shown to Males at 14 ms achieved a significantly lower score than expected (a correctness score of 3.55, $p < 0.001$, where they were expected to achieve 3.70, the summation of the Contralateral and the Male terms in the model). Similarly, Contralateral conditions at 28 ms for Females were lower than expected (achieved correctness score$= 3.70$, $p < 0.01$ whereas Females were expected to achieve a correctness score around 3.80). In other words, these two results combined show that Females performed relatively better than Males for Ipsilateral targets presented at 14 ms.

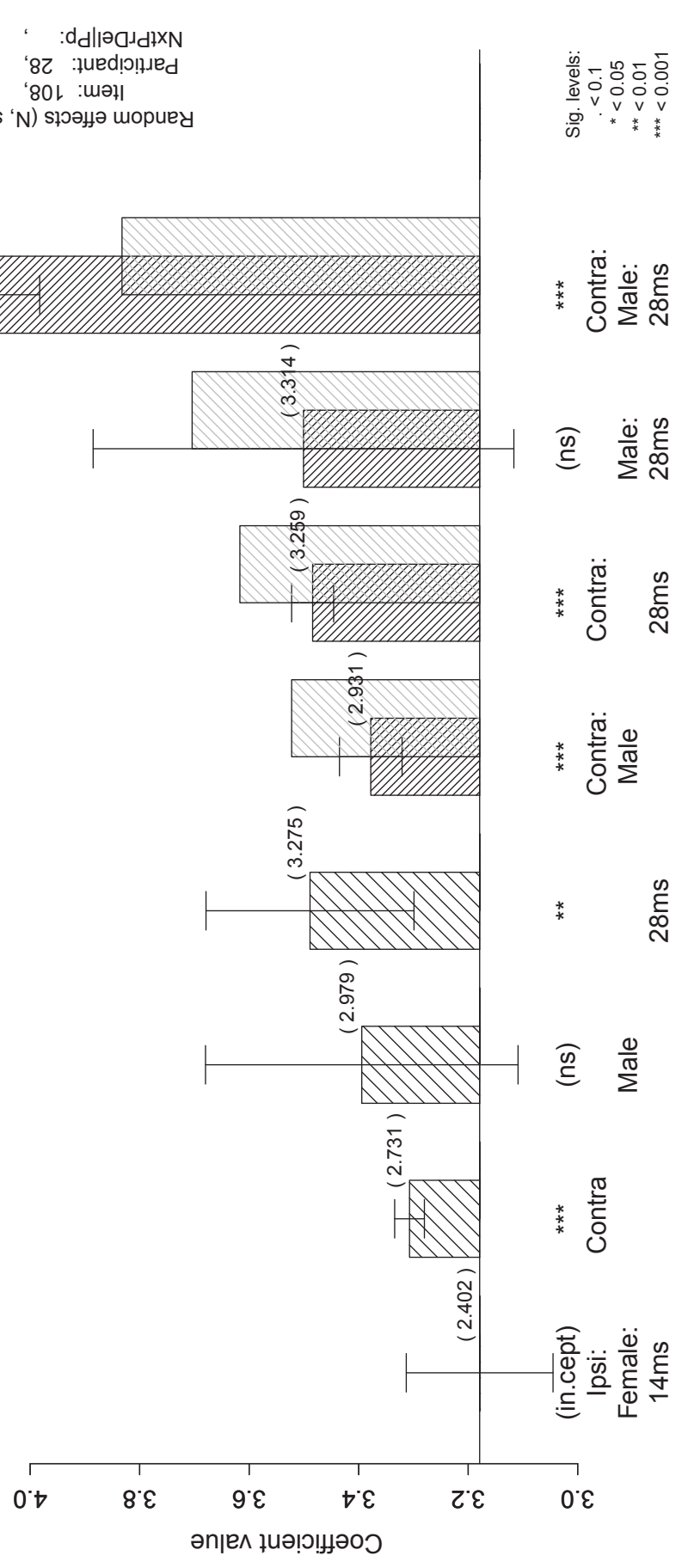


Figure 3.16: Plot of LMER model for Correctness (the comprehensive data, with $Correct$ scores from 0 through 4), for the Ipsilateral and Contralateral experiment conditions, for Females and Males and with stimuli presentation durations of 14 and 28 ms, and for all interactions of these fixed terms. The model equation (Model 3.6) is shown in Fig 3.15.

The last two bars in Fig. 3.16 contrast Male performance at 28 ms from their performance at 14 ms. That is, Males achieved a significantly lower correctness score for Ipsilaterally presented stimuli at 28 ms (correctness$= 3.70$, $p < 0.001$ versus an expected score of 3.85), and achieved a higher correctness score than expected for Contralateral conditions presented for 28 ms (correctness$= 4.28$, $p < 0.001$, versus an expected correctness score of 4).

Thus, my observations from Table 3.15 that Females perform relatively better in Ipsilateral conditions at short presentation durations and Males perform relatively better in Contralateral conditions at longer presentation durations is borne out by the LMER model (Model 3.6).

## 3.7 Exp. II. Could a contralateral or ipsilateral preference be mediated by reading abilities?

The purpose of this experiment was to determine if language measures associate with either a Contralateral or an Ipsilateral preference. As such, the experiment procedure was a repeat of Experiment **I**, together with the testing of various language measures.

### 3.7.1 Participants

I recruited twenty university students with non-poor reading abilities who had performed background reading tests from a previous eye-tracking experiment that I helped run and analyse.[13] However, the requirements for the eye-tracking experiment were slightly different from the requirements for my Exp. **I**: the participants were asked to be right-handed and have at least one good eye for reading (and not be dyslexic). I have asked the participants in Exp. **I**to have good eyesight in both eyes. Unfortunately, a portion of the participants did not have good vision in both eyes and hence performed poorly in this Experiment.

### 3.7.2 Materials and procedure

This experiment used the same materials and procedures as Exp. **I** (shown schematically in Figure 3.3). The only addition to the data is that the participants in this experiment also have a collection of reading measures (described below). I used the same procedure as described for Exp. **I**.

#### 3.7.2.1 Reading measures

The reading measures I used were chosen for the eye-tracking experiment to help distinguish dyslexic readers from participants with normal or better reading abilities. While

[13]The result of this collaboration with Dr. Manon Jones was published in *Cognition*(Jones, Obregón, Kelly, and Branigan, 2008).

they do not constitute a full battery of possible language tasks, they do address several theoretical questions:

- Could the Contralateral advantage be the result of some anatomical construct related to some non-verbal ability (measured by the WAIS block design task (Wechsler, 1997))?
- Could the Contralateral advantage associate with some statistical property related to vocabulary expertise (measured by the Vocabulary section of the WAIS (Wechsler, 1997))?
- Could the Contralateral advantage relate to some anatomical construct empowered by phonological processing abilities? Specifically, I tested phonemic decoding (measured by a nonword reading test (Lum, Cox, Kilgour, Snowling, and Haywood, 2005)), and whole-word recognition (measured by an exception word reading test (Manis, Seidenberg, Doi, McBride-Chang, and Petersen, 1996)). I also used a standardised word recognition test to see if it specifically associated with Contralateral or Ipsilateral presentations of the stimuli (the word recognition section of the Wide Range Achievement Test-3 (Wilkinson, 1993)).
- As participants have to recall what they have seen (the image is no longer visible when they give their response), could short-term memory or working memory empower a Contralateral advantage? Hence, I measured forwards and backwards digit span tests (Miles, 1997).

I added each measure into the base model (Model 3.3) to first see if it explained a significant proportion of variance, and then as a term interacting with experiment condition, to see if it specifically explained variance with either the Contralateral or Ipsilateral conditions.

### 3.7.3 Results

Of the 20 participants, five were removed from analysis: three could not complete the Haploscope experiment because of visual difficulties, one needed 57 ms stimuli presentation durations to perform the task[14], and one was removed because they only got a few correct in the Both condition. Consequently, the results are from 7 males and 8 females, all classified as right-handed by self-report.

I applied the model of probability of correct response from Exp. **I** (Model 3.3) to this data and found the same pattern of results, but the Contralateral advantage was not significant with just 15 participants (Fig 3.17).

[14] I only used participants who could perform the experiment with either 14 or 28 ms presentation durations

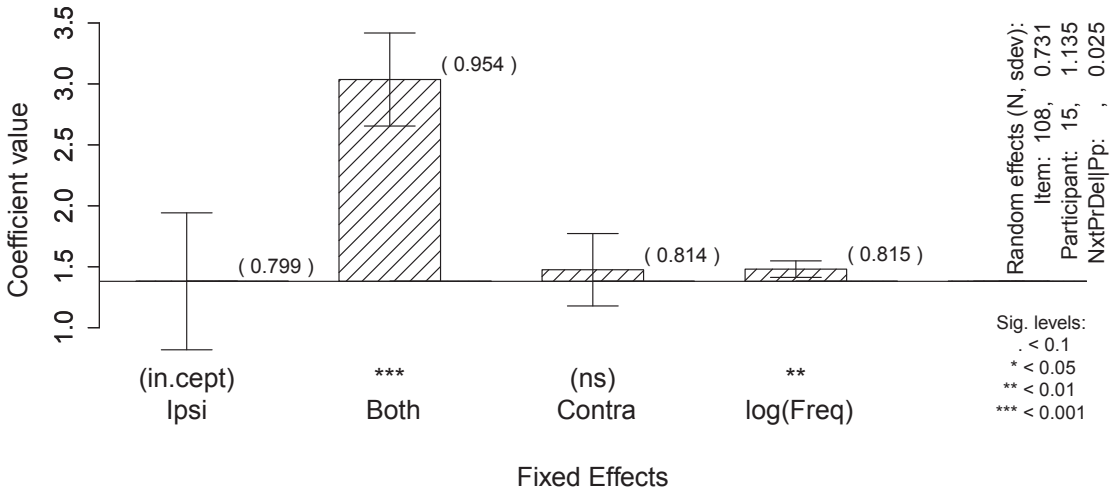


Figure 3.17: Plot of LMER model for correctly identified targets for Exp. **II**, using Model 3.3 from the previous experiment. While the same trends can be observed in both LMER results, the Contralateral coefficient for this experiment is not significant. A possible cause for this could be the smaller number of participants (15 in this experiment versus 28 in Exp. **I**).

In this experiment I found that there were no single effects from non-verbal or verbal ability (the WAIS block design and vocabulary tests, respectively) or from phonemic ability as measured by the exception word and nonword tests (see Table 3.16).

I found that scoring highly on both block design and vocabulary together (i.e., the interaction term of the two variables) explained a significant portion of the variance. However, when WRAT3 word recognition was entered into the model, it explained a significant portion of the variance and left block-design and vocabulary with non-significant contributions. That is, whereas a higher overall intelligence quotient score accounts for better perception accuracy, this is subsumed in people's ability to correctly read words. However, none of these measures interacted any of the three experiment conditions.

As could be expected from the nature of this experiment where participants had to answer from memory, a portion of the variance was explained by memory span. Interestingly, whereas a larger score on the Digit-forward test associated with a larger probability of correct target recognition, the inverse of the Digit-reversed score associated with greater probability of correct report (Fig. 3.19). Furthermore, the interaction of these two memory tests explained a significant proportion of the variance. That is, whereas a greater forward digit span memory aided in correct report, a poorer performance on the Digit-reversed test associated with correctness of target perception. Perhaps the ability to decompose the visual stimuli into individual letters lends to confusion of what the

Table 3.16: Probability of correct responses, with Language measures included as independent predictors.

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Ipsi | 1.2395 | 1.2395 | 0.1850 | 6.6987 | |
| 1 | Both | 2.9100 | 1.6705 | 0.1941 | 8.6075 | *** |
| 2 | Contra | 1.3184 | 0.0789 | 0.1514 | 0.5214 | (ns) |
| 3 | log(Frequency) | 1.3391 | 0.0995 | 0.0340 | 2.9312 | ** |
| 4 | Block design | 1.2948 | 0.0553 | 0.0867 | 0.6376 | (ns) |
| 5 | Vocabulary | 0.8711 | -0.3685 | 0.2822 | -1.3057 | (ns) |
| 6 | Nonword | 1.1587 | -0.0808 | 0.1202 | -0.6723 | (ns) |
| 7 | Exception word | 1.3120 | 0.0724 | 0.2878 | 0.2517 | (ns) |
| 8 | Word recognition | 1.3918 | 0.1522 | 0.0376 | 4.0432 | *** |
| 9 | Digit-Forward | 1.7083 | 0.4688 | 0.1010 | 4.6410 | *** |
| 10 | Digit-Back | 1.0678 | -0.1717 | 0.1945 | -0.8828 | (ns) |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Target | 108 | 0.5204 | 0.7214 |
| Participant | 14 | 0.5426 | 0.7366 |
| NxtPrDel\|Pp | | 0.0018 | 0.0430 |

$$
\begin{aligned}
Correct\{\text{no},\text{yes}\} \sim\ & Condition\{\text{Ipsi},\text{Both},\text{Contra}\} + \\
& \log(Frequency) + \\
& Word\ recognition + \\
& Digit\ forward * \\
& \text{inverse}(Digit\ reverse) + \\
& (csrNextPressDelay \mid Participant) + \\
& (1 \mid Target), \\
& \text{model} = \text{binomial}
\end{aligned}
\tag{3.7}
$$

Figure 3.18: Model equation for four-letter probability of correct perception by Both, Contralateral and Ipsilateral conditions and with language measures.

target word should be. Nevertheless, none of the memory tests associated specifically with either Both, Contralateral or Ipsilateral experiment conditions.

The model for the best-fit LMER equation is shown in Fig. 3.18 and plotted in Fig. 3.19. Note that the language measures only add separate contributions to the original model (Model 3.3) that do not interact with the experiment conditions.

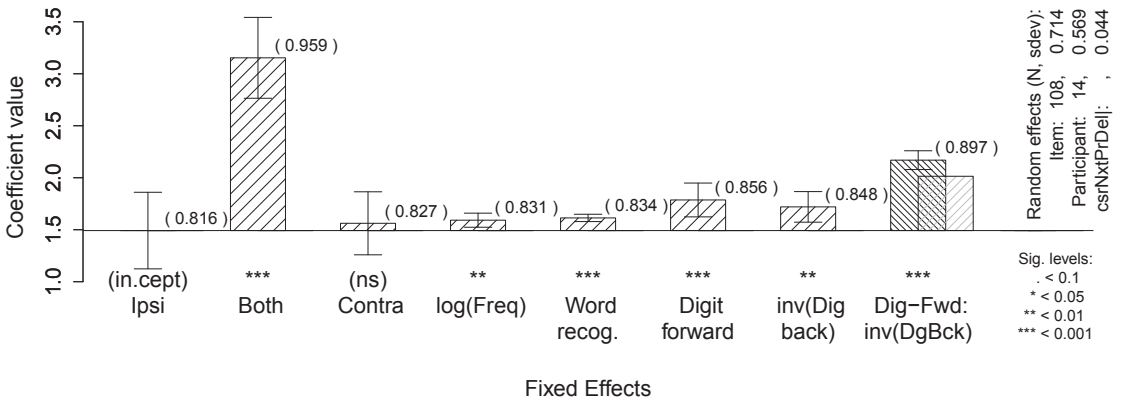


Figure 3.19: Plot of LMER Model 3.7 for probability of correct report for four-letter targets, including all language measures that significantly explain variance. However, none of the language tests associated with neither Both, Contralateral or Ipsilateral experiment conditions.

## 3.8 Discussion

In this chapter I test the hypothesis that the contralateral visual fields of the two eyes perform differently from the ipsilateral visual fields, with respect to word recognition when the words are projected wholly into the two foveae. That is, cognitive performance is different when the same information is projected exclusively either to the contralateral visual fields or to the ipsilateral visual fields.

To test this, I successfully developed and validated a new psycholinguistic methodology with a Haploscope, a type of mirror stereoscope. The key aspect of this tool is that the observer is limited to a single fixation on text that is presented completely within the disc of the fovea (i.e., within 0.5 degree of arc from where the eye is fixated), for each eye separately. I accomplish this with very accurate and very short stimuli presentations while the observer is relaxedly concentrating on a fixation cue, with high quality text on a screen that is far enough from the observer to assure that the stimuli images remain within a disc that is 1 degree of arc in diameter and centred on the fixation cue (see Fig. 3.2). Also, I immediately show a back-mask that completely covers the possible regions where the stimuli are presented, so as to limit the known retinal after-image effect.

The participant is asked to say what they saw. However, the short presentation and the back-mask make this task challenging. That is, the dependent variable in this procedure is accuracy of report. I purposefully make the task as hard as possible such that the observer can still make a proportion of correct reports.

As people vary widely in their ocular abilities, I give a pre-test in which the stimuli are presented for different amounts of time: 28 and 57 ms. If participants manage

to accurately perceive the targets at 28 ms, I then administer the test with 14 ms presentation durations. I found that most of my participants could perform satisfactorily at either 14 or 28 ms.

As accuracy levels vary widely between participants, I resorted to analysing my data with Linear Mixed Effects regression models. This statistical modelling tool allows me to model each participant separately and at the same time, assign variance to the fixed terms in the linear model by means of Maximum Likelihood estimation. In particular, this tool allows me to analyse repeated measures data where each participant is given all experiment conditions. The participant in this model is referred to as a random effect. Furthermore, as each target word might have an unique effect (like the shapes of its end letters that are not captured by properties like written frequency), I also model each target as a random effect within the LMER model.

I asked participants to report what they felt they had seen (after each target presentation) and I typed their response into the computer. This allowed me to carry out an analysis of their naturalistic responses by coding each response in terms of what letters they named correctly. This was performed by an AWK script on the entire data set and before I carried out the statistical modelling of the data. With this rich data set I carried out my fine-grain analyses of cognitive performance under different experiment conditions, for both exactly correct and partially correct responses, taking into account individual differences between participants.

For the exactly correct analyses, I found that full words shown to both eyes are readily identified (the *Both* experiment condition). When the target is shown as two half-words to the two eyes, words shown in a contralateral manner are more likely to be perceived than words shown in an ipsilateral manner. Namely, $Both \gg Contralateral > Ipsilateral$. In terms of probability of correct response (and irrespective of actual presentation duration or the other observables I recorded), the *Both* condition is correctly perceived in about $94\%$ of the trials, the *Contralateral* condition is correctly reported about $66.2\%$ of the time, and the *Ipsilateral* condition is correctly recognised in about $58.7\%$ of the trials (Fig. 3.8). That is, the *Contralateral* condition was about $7.5\%$ more accurately reported than the *Ipsilateral* condition; furthermore, this difference is statistically significant with a two-tailed Z-score comparison, $Z = 2.9$, $p < 0.01$. Hence, I have validated my hypothesis that I could find this difference for words presented wholly within the fovea, and thus providing further evidence for a vertically split fovea.

I also found large differences between participants, both in terms of the amount of time they needed to perform the task (Table 3.6) and in the range of total correct scores they each achieved (Fig. 3.5). Furthermore, I found that I could refine the random effect model for Participant with the amount of time they took to press the "ready" buttons for the next trial. That is, participants appeared to press the "ready"(i.e., ready for

the next trial) buttons more quickly when they felt that they had correctly perceived the target than when they felt that they had responded incorrectly to the current trial. This continuous measure refined the error variance model significantly (Table 3.9). I regard this finding as a confidence measure that highlights the power of working with a fine-grained data set.

I analysed partially correct responses to see if there was any special manner in which participants were performing the task that could be extracted from the letters (in their ordered position) that were correctly identified. Since each bigram was presented uniquely to a different visual field in the *Contralateral* and *Ipsilateral* experiment conditions, I could contrast anatomical structures in terms of correctness of report.

In terms of hemispheric organisation, I found that the beginning bigrams were almost twice as correctly reported than the ending bigrams (Fig. 3.11), implying the the RH has some trait to better identify word beginnings than the LH to identify word endings. When I took Sex into account (Fig. 3.12), I found that Females performed differently from Males: whereas Females achieved a larger difference between RH and LH correct bigram identifications in ipsilateral projections (highlighting a preference for the ipsilateral channels in Females), Males achieved a larger difference between RH and LH correct bigram identifications in contralateral projections, highlighting a preference for the contralateral channels in Males.

While this post-hoc analysis does not address my initial hypothesis, it does point to possible refinements in anatomical organisation related to the contralateral versus ipsilateral division of labour. I will look at this in more detail in Chapter 5.

When participants do not manage to make a correct identification, there is a significant improvement in performance in the Contralateral condition when they have more time to observe the stimuli over Ipsilateral conditions with longer presentation durations (Fig. 3.14). In the same vein as the Both condition duplicating the available visual information, perhaps the Contralateral channels manage to transfer more information than the Ipsilateral channels, an advantage that is amplified by having more exposure (i.e., a longer presentation duration) to the stimuli.

The comprehensive set of results (that is, exactly correct, partial word identifications and erroneous reports) were used to test the hypothesis that the contralateral channels associate with better performance than the same information relayed through the ipsilateral channels. Furthermore, and due in part to the greater amount of fine-grained data, a new dissociation emerged: Whereas Females performed better than Males on the Ipsilateral condition at the shorter presentation duration, Males performed better than Females on the Contralateral condition at the longer presentation duration. This could be the result of anatomical differences between contralateral and ipsilateral channels between Males and Females. I address this issue further in Chapter 5.

In relation to Exp. **II**, high-level cognitive function associated with general intelligence measures do not explain word perception, nor do they share specific variance with either Contralateral or Ipsilateral conditions. Rather, the ability to recognise words (of different lengths and of different levels of phonological complexity) explains a significant portion of the variance in this experiment. Nevertheless, phonological tests (in the form of exception words or non-words) do not explain any variance in the model.

Memory tasks (in the form of digit span tests) explain a significant portion of the variance. This is expected, as the participants have to provide their response after the stimuli have been removed from the screen. However, what is interesting is that the inverse of the digits-reverse tests proves to be significant: as if being able to decompose and manipulate the sub-parts of the stimuli rather confuses participants. Again, this is a low-level cognitive function as opposed to a high-level general cognitive ability.

The two experiments presented in this chapter point to the Contralateral preference being mediated by low-level cognitive abilities and not high-level language function. This extends the Toosy et al. (2001) findings of greater Contralateral activation by showing that just the foveal area of the retina is capable of producing a Contralateral advantage.

One issue that emerged from these two experiments is that the nature of word beginnings and word endings could play a significant role in overall word perception.

## 3.9 Chapter conclusions

I have carried out a novel experiment to test the hypothesis that lexical information in the contralateral visual fields (specifically, visual information from words landing within each nasal hemifovea) is more likely to be correctly identified than the same information in the ipsilateral visual fields (i.e., landing on the temporal hemifovea). Linear Mixed Effects regression analyses on the fine-grained correctness-of-perception shows that this is a useful tool to decouple between-participant variability from generalisable trends in performance across participants. I found that my hypothesis is supported by this experiment; namely, that words are 8% more likely to be recognised when shown as half-words to the contralateral visual fields than when the half-words are shown to the ipsilateral visual fields. I also found a contralateral advantage when participants did not manage to correctly identify the target word. There was a three-way interaction between experiment condition, Sex and stimuli presentation duration: whereas females showed larger correctness score gains in Ipsilateral presentations, males managed greater correctness gains in Contralateral presentation, when the participants had more time to view the targets. Furthermore, the Contralateral advantage does not associate with phonological decomposition (nonword or exception word tests), or general high-level cognitive ability (the blocks design test or the vocabulary test). Performance was generally improved by better working memory (digit-forward) and by better word recognition.

This argues for a low-level cognitive function for the contralateral and ipsilateral channels that is not mediated by high-level linguistic abilities. Overall, I found that a split-fovea hypothesis is supported by these findings. An asymmetric performance in word perception between the contralateral and ipsilateral modes of presentation implies that there is a difference between the hemifovea; in summary: $Both \gg Contralateral > Ipsilateral$.

# Chapter 4

# Conjoint, crossed and uncrossed visual fields in the haploscope

## 4.1 Chapter overview

Binocular eye-tracking experiments on reading connected text have shown that participants make fixations that are either conjoint, crossed fixation disparity or uncrossed fixation disparity. The purpose of the following chapter is to explore this behaviour with the haploscope to see how each of these conditions facilitate the perception of text. I arranged the stimulus materials so that I could have one-letter disparity (either crossed or uncrossed) as well as conjoint conditions when incomplete words were shown to each eye.

The first two experiments explored this with only contralaterally designed materials: the first by testing accuracy of visual perception under challenging conditions, and the second by means of a classical lexical decision task. The third experiment extended the first by adding ipsilaterally presented stimuli.

## 4.2 Introduction

Recent binocular eye-tracking experiments have shown that most adult readers make disparate –not conjoint– fixations on text under normal reading conditions(Juhasz, Liversedge, White, and Rayner, 2006; Liversedge, Rayner, White, Findlay, and McSorley, 2006a; Liversedge, White, Findlay, and Rayner, 2006b; Nuthmann and Kliegl, 2009; Shillcock, Roberts, Kreiner, and Obregón, 2010)That is, the two eyes typically focus on slightly different locations in the text. Either the left eye is fixated on a location to the right of the right eye (a crossed fixation disparity)[1], or the left eye is fixated on a location to the left of the right eye (an uncrossed fixation disparity); they are relatively rarely fixated on the same location in text (a conjoint fixation).

The statistical nature, the combinatorial complexity and the repetitiveness of the reading process –the sheer number of binocular fixations on a large amount of both

[1]N.B. This is a different usage of the terms "crossed" and "uncrossed" as that found in classic optometry literature, where crossed and uncrossed refer to retinal disparity and not fixation disparity.

differing and similar written words– entrains the processor to make eye fixations that are statistically optimal for it to perceive both old and new text. Thus, I assume that the processor purposefully moves the eyes in such a manner so as to produce either conjoint, crossed or uncrossed fixations during reading. If one of these situations were preferred (i.e., occurs more frequently), there would be particular reasons at to why so, with one possible reason being simply that this favoured binocular disparity confers greater accuracy of visual perception.

The question I address in this chapter is whether there could be a perceptual advantage for either crossed or uncrossed fixation disparities. I decided to explore this with the haploscope, as the question concerns visual perception of written text and my previous experiments have shown the haploscope to be a fine-grained tool capable of exploring visual perception of words.

## 4.3 Exp. III. Contralateral haploscope presentations of conjoint, crossed and uncrossed single words: Accuracy of perception

As I needed a method of ensuring that the recognised word was the result of both eyes and not of a single eye being responsible for the accuracy of report. I accomplished this by showing incomplete targets to each eye such that the combination of information from both eyes would provide all correctly-placed letters in the target; no single eye would be should the complete target. As the binocular eye-tracking studies above found that most binocular disparity is of the order of one or two letters, I designed my materials to provide one letter's worth of disparity between the two eyes. I could achieve this by moving stimuli strings by half a character in each eye and having experiment conditions where the letters overlapped in space across the two eyes and still occupied only one degree of horizontal visual angle in total (so as to fit the projection of stimuli within the fovea). However, I would not manage to show all letters in all conditions if I only used half-field presentations like in Experiment **I**. Specifically, the middle letter would not be shown in an Uncrossed condition (see Figure 4.1), and the same middle letter would be repeated in both eyes in a Crossed condition. Thus, to balance the two conditions as much as possible and still have some information shown to only one eye or the other, I chose to leave out only the outer letter and show the same four other letters of five letter words to each eye in all conditions. This way, all letters in the word were shown across the two eyes and yet no eye was shown the full target string.

I also wanted to avoid the tendency for participants to try to guess words from only the few letters they could identify. Hence, I added a few non-words and modified my

instructions to say, "If you see a word, please say it. If you see only a few letters, please tell me what letters you see. Not all strings are words."

As a wider distance between the eyes would imply larger incident angles pointing in to the attended fixation locations, there is a possibility that the processor could use this extra information to determine depth and thus better control angular disparity between the eyes. To test for this, I measured the distance between the eyes to see if this accounted for any variance in the statistical models.

### 4.3.1 Design, methods and participants

From pilot testing of the conjointly presented stimuli, I found that above 100 ms participants would tend to report an unclear overlapping of text instead of a clear word, Hence I chose to show the stimuli at the next screen refresh rate down from this, at 85 ms. As I have already found that the contralateral presentation of text is probabilistically more correctly reported, I chose to show the stimuli in a contralateral manner, namely that the beginning letters would be shown to the left eye and the ending letters would be shown to the right eye (exemplified in Figure 4.1); that is, putting more visual information in the contralateral visual hemifields. As in the Contralateral condition in Experiment **I**, I generated the stimuli by removing the outer letter from the target in each eye so that no eye was shown the full target word. Hence, the letters from both eyes were needed in order to be shown all letters in the target.

All the targets were prepared to be shown in the three experiment conditions: $(i)$ Conjoint fixations, where three letters completely overlapped between the two eyes relative to the fixation cue; $(ii)$ Crossed fixations, where the letters were arranged with respect to the cue such that the left eye would be focusing on the space between the third and fourth letters and the right eye would be focusing on the space between the second and the third letters; and $(iii)$ Uncrossed fixations, where the left eye would be focusing on the space between the second and the third letters, and the right eye would be focusing on the space between the third and fourth letters. These layouts of the stimuli with respect to the cue for each eye amount to either conjoint fixations, crossed fixations with one letter crossed disparity between the eyes, or uncrossed fixations with one letter uncrossed disparity between the eyes. For example, for the target `"table"` the Conjoint fixation condition was shown as (`tabl_`)(`_able`)[2]; the Crossed fixation condition was shown as (`tab|l_`)(`_a|ble`); and the Uncrossed fixation condition was shown as (`ta|bl_`)(`_ab|le`). These three experiment conditions are shown in Figure 4.1. As in Experiment **I**, the difference in the three stimuli were not the letters shown to the eye, but in the placement of the letter strings with respect to the gaze fixation

[2]The contents of the two sets of parentheses "()()" represent what is shown to the two eyes; the "_" represents the missing letter, and the highlighted letter or "|" represents the relative placement of the broken vertical cue line in each eye.

position. At most there was a difference of one letter of horizontal displacement between the Crossed and Uncrossed conditions.

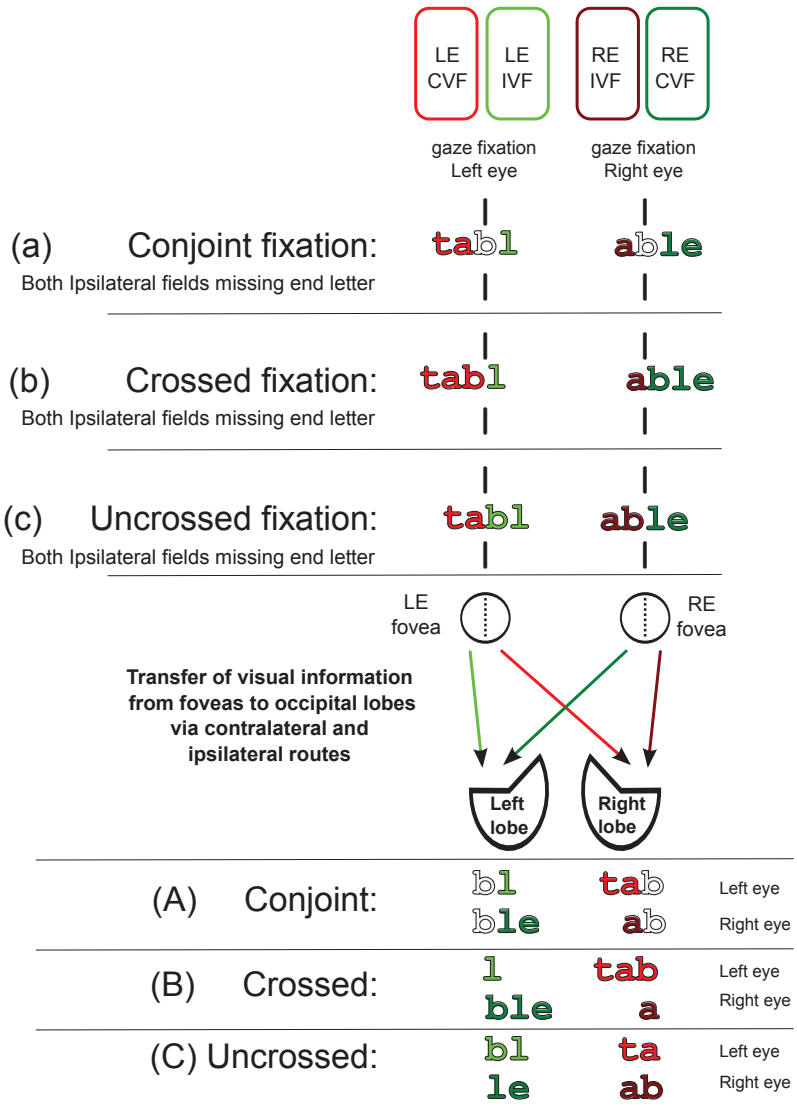


Figure 4.1: Experiment design for conjoint, crossed and uncrossed fixation disparities. Only contralateral presentations were used; that is, while the contralateral visual fields (CVF) contained all letters, the ipsilateral visual fields (IVF) were missing their respective outer letter.

I selected 64 high frequency and 64 low frequency words from the MRC corpus (Wilson, 1988), and 18 phonologically regular non-words. I constructed a within-subject three-way Latin Square experiment (targets were shown either in Conjoint, Crossed or Uncrossed manners) in EPrime, as in Exp. I.

The experiment was administered in a manner similar to Exp. I, except that there was no pre-test to select the stimuli presentation duration as everyone saw the stimuli for 85 ms. I chose not to administer the stimuli at different presentation durations as

the crossed and uncrossed stimuli were quite challenging in pilot testing, even with the larger 85 ms presentation duration.

As before, first the participants carried out the E-Prime experiment and then I administered the background questionnaires (including the additional measurement of the distance between the pupils). The E-Prime experiment was broken into two parts to give the participants a rest. As before, the participant was seated comfortably with a five button button-box on their lap in a darkened room. For each trial, first a broken vertical cue was shown to each eye in an untimed manner and the participant was instructed to look at "the cue" and wait until they felt that the cue was clearly in focus, at which point they were to bimanually press the two outer buttons on the button box. After a short random delay (200 to 300 ms), the cues disappeared and the stimuli were simultaneously shown to the eyes for 85 ms (in a pale grey –RGB:190,190,190– Bold Courier New 24 point font). Immediately after this the stimuli were replaced by a centred seven character (#) back-mask for 29 ms (in a slightly darker grey but otherwise same font as the stimuli), and then a black screen for an indefinite amount of time. The participant then said what word they saw (I would ask for spelling clarification for phonologically ambiguous words), or if not, what letters they saw. I then typed their response into the computer, and a new trial would start. While the full five letter target subtended 1.17 degrees of arc, each eye only saw four letters, with at most three letters extending horizontally from the cue and giving a maximum horizontal angle of 1.4 degrees of arc between the two ends of the stimuli.

Participants were university students (fluent English speakers from an early age) who signed a consent form and were paid an hourly rate for their participation.

### 4.3.2 Results

After 11 participants there was a pattern in the data (Fig. 4.2, showing proportion of responses with all five letters correct) showing that, while the participants were performing comparably on Conjoint and Crossed conditions, they were less than half as accurate in the Uncrossed condition.

An *LMER* statistical model confirmed that the Uncrossed condition was significantly less accurately reported than the Conjoint or Crossed conditions (Table 4.1). In this table, both the Conjoint (line 0) and Crossed (line 1) conditions were more than 90% accurately reported and not statistically different from each other. In contrast, the Uncrossed condition (line 2) was only correctly reported about 44% of the cases and statistically different from the Conjoint case $(\mathrm{Zscore} = -15.1, p < .001)$.

To investigate possible implications of the Contralateral-only method of presentation, I developed a more complete version that included both contralateral and ipsilateral modes of presenting the stimuli (Exp. **V**).

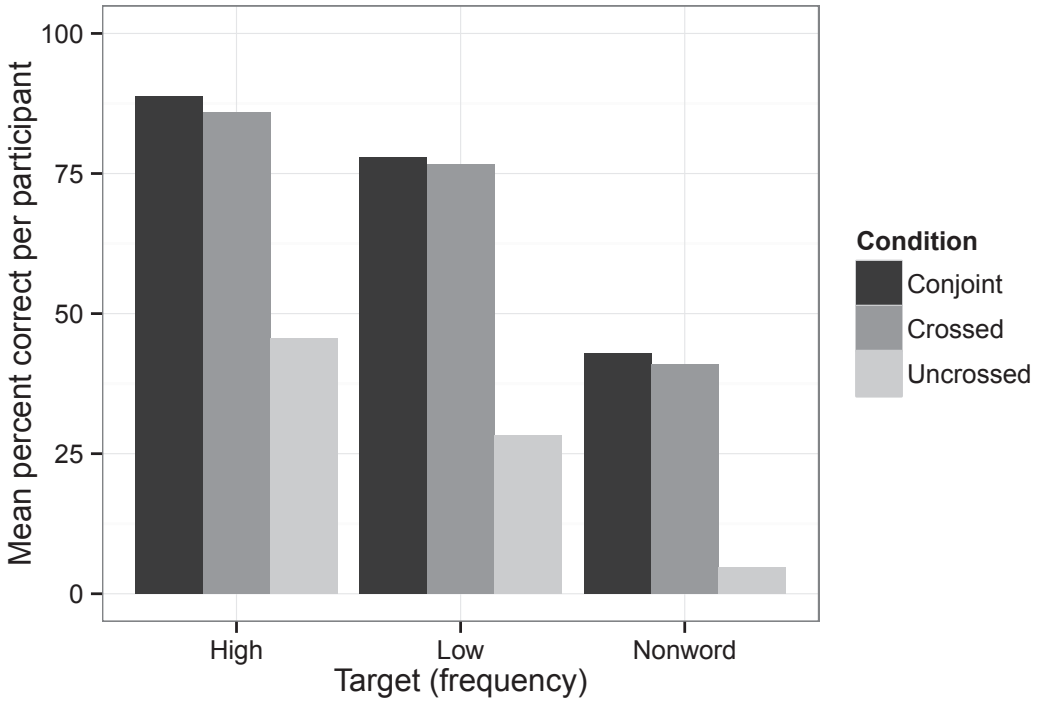


Figure 4.2: Proportion of correct target responses for Conjoint, Crossed and Uncrossed fixation disparity conditions, for words and nonwords. Stimuli presentations were all in the contralateral manner.

$$
\begin{aligned}
Accuracy\{\text{Incorr}, \text{Corr}\} \quad \sim \quad & FixationCondition\{\text{Conjoint}, \text{Crossed}, \text{Uncrossed}\} + \\
& TargetFrequency\{\text{High}, \text{Low}, \text{Nonword}\} + \\
& (1 \mid Participant) + (1 \mid Target), \\
& \text{model} \; = \; \text{binomial}
\end{aligned} \tag{4.1}
$$

Figure 4.3: Model equation for Conjoint, Crossed and Uncrossed fixation conditions in the Contralateral presentation format (Exp. **III**).

## 4.4 Exp. IV. Contralateral haploscope presentations of conjoint, crossed and uncrossed single words: Lexical decision

The lexical decision task has been key for psycholinguistics research in showing RT differences between experiment conditions and extrapolating from these the relative loads on the processor for different types of linguistic features. However, how does the accuracy of visual perception compare to RT using the Haploscope? The following

Table 4.1: Visual perception: LMER model for probability of perceiving all five letters correctly in Exp. **III**.

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Conjoint and High frequency | 91.6% | 2.3942 | 0.3337 | 7.1751 | |
| 1 | Crossed | 90.7% | -0.1147 | 0.1754 | -0.6543 | (ns) |
| 2 | Uncrossed | 43.4% | -2.6590 | 0.1743 | -15.2521 | *** |
| 3 | Low frequency | 82.4% | -0.8475 | 0.1640 | -5.1678 | *** |
| 4 | Nonword | 38.1% | -2.8791 | 0.2530 | -11.3799 | *** |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Target | 155 | 0.1951 | 0.4417 |
| Participant | 11 | 0.9068 | 0.9523 |

experiment repeats **III** as a lexical decision task to see if there were reaction time differences between conjoint, crossed and uncrossed presentation modes.[3]

### 4.4.1 Design, Methods and participants

The stimuli were prepared as in Exp. **III**: four letters from five letter targets were shown to each eye such that the combination of the two eyes would provide the full target. As before, the stimuli were constructed in the contralateral manner, where the four first letters were shown to the left eye and the four last letters were shown to the right eye. Twenty four high frequency and twenty four low frequency five letter words from the MRC corpus (Wilson, 1988), and forty eight phonologically regular nonwords were chosen for this lexical decision task. A Latin Square design was used to ensure that all targets were presented in all three experiment conditions.

The timings in the experiment were chosen such that each trial initiated with a 1000 ms plus a random extra time between 200 and 300 ms presentation of the vertical cues for each eye. The cues were replaced by the stimuli in each eye which stayed on for six screen refreshes (85 ms). The stimuli were then replaced by a black screen for an indefinite amount of time, until the participant made a bimanual button press to select their choice of Word or Nonword for the target. The participant was given a 1000 ms break before the next trial started. Forty university students took part and signed consent forms, and were paid for their participation.

The main difference with the visual perception experiment (Exp. **III**) was in the task that the participants had to carry out and how they provided their responses. Exp. **III**

[3]I thank Natasha Dare for building the E-prime experiment and running the participants.

allowed the participant to freely view the two cues until they felt that they were "clearly in focus" and ready to be shown the stimuli. In contrast –following standard practice with lexical decision tasks–, this version of the experiment did not allow participants to wait until they felt ready and instead only gave them 1 second to view the two cues.

### 4.4.2 Results

A total of 36 participants took part in this lexical decision experiment. In terms of accuracy for the word/nonword classification (Fig. 4.4), the Conjoint condition showed that participants were performing the task (with mean accuracy=84%, sd=15) and that the haploscope experiment design of splitting word fragments across the two eyes was functioning as expected, with lexical decision categorisation in the Crossed condition similar to the Conjoint condition. However, participants were only performing at chance levels in the Uncrossed condition for word targets while categorising nonword targets almost as correctly as the Conjoint or Crossed nonword cases.

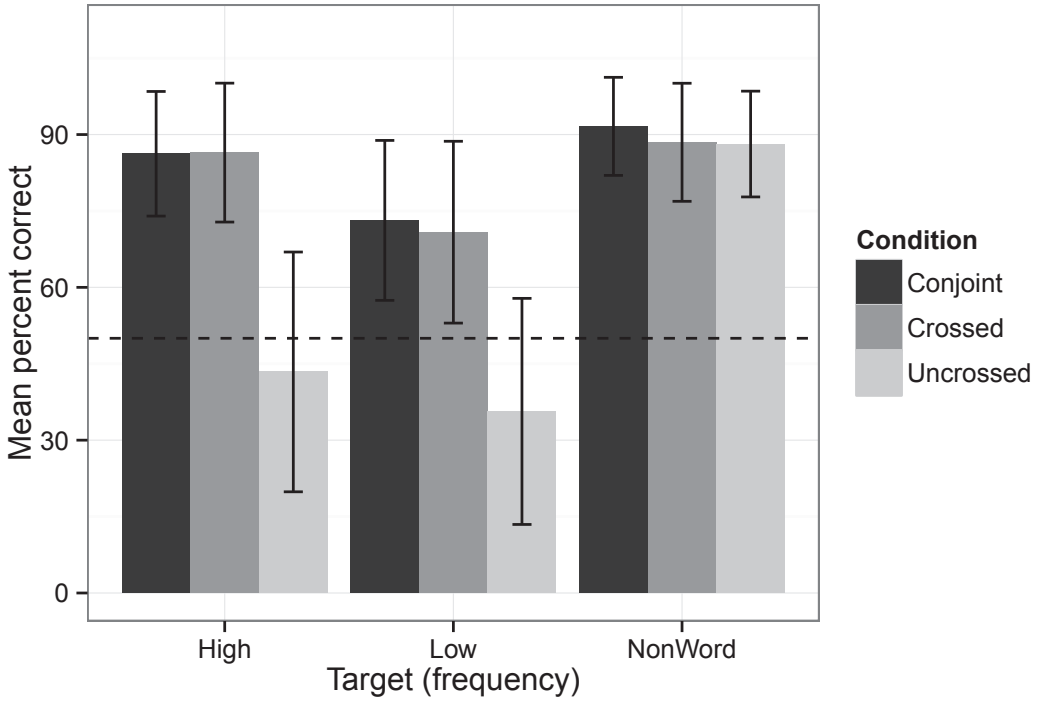


Figure 4.4: Lexical decision: Mean percent correct responses. Chance level is represented by the dashed line.

In terms of RT, Table 4.2 shows an LMER model for log(RT) of correct button responses (Model 4.2). The Conjoint low frequency words (Line 3, predicted RT=841 ms) took significantly more time than the Conjoint high frequency words (Line 0, predicted RT=742 ms), with $\mathrm{T} = 5.43$ and $p < 0.01$. This is as expected from typical lexical decision experiments that show an extra delay for low frequency words.

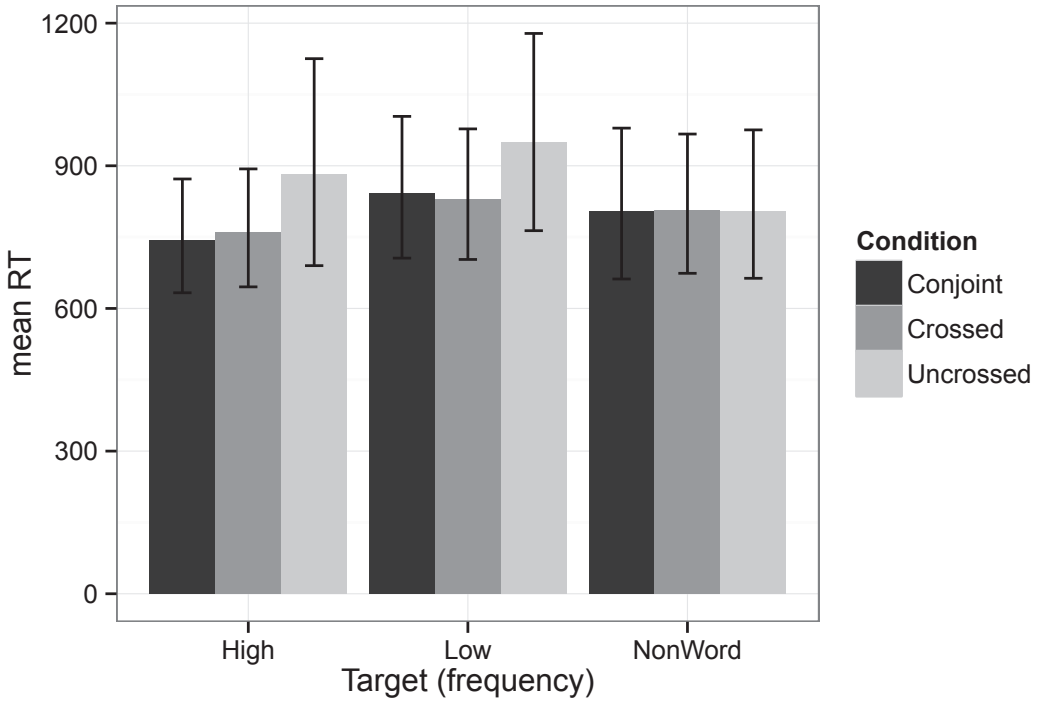


Figure 4.5: Lexical decision: Mean reaction times (calculated as: $\exp(\text{mean}(\log(RT)))$) for correct responses for conjoint, crossed and uncrossed fixation disparities, and for high and low frequency words and for nonwords.

$$\begin{aligned} \log(RT) \sim\ & FixationCondition\{\text{Conjoint}, \text{Crossed}, \text{Uncrossed}\} * \\ & TargetFrequency\{\text{High}, \text{Low}, \text{Nonword}\} + \\ & (1 \mid Participant) + (1 \mid Target), \\ & \text{model} = \text{gaussian} \end{aligned} \tag{4.2}$$

Figure 4.6: Lexical decision: Model equation for the Conjoint, Crossed and Uncrossed conditions (Model 4.2).

Interestingly, the Crossed condition was not significantly different from the Conjoint condition, for either high or low frequency words (as can be seen in Fig. 4.5). Line 1 vs. line 0 from Table 4.2 shows the comparison of the Crossed condition to the Conjoint condition for high frequency words, and line 5 vs. line 3 shows the low frequency model predictions of RT of 828 ms and 841 ms, respectively (the are statistically non-significant, T-test not shown).

For the Uncrossed conditions, participants took significantly longer for word targets than in both Conjoint and Crossed conditions, but not for nonword targets (Fig. 4.5). Line 2 vs. line 0 shows the comparison for high frequency words between the Uncrossed and Conjoint conditions, with model prediction RT of 849 ms vs. 742 ms respectively

Table 4.2: Lexical decision: LMER model for Reaction Times (Model 4.2)

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | t value | |
|---|---|---|---|---|---|---|
| 0 | Conjoint and High frequency | 742.1119 | 6.6091 | 0.0319 | 206.9627 | |
| 1 | Crossed and High frequency | 754.4583 | 0.0170 | 0.0155 | 1.0606 | (ns) |
| 2 | Uncrossed and High frequency | 849.5442 | 0.1362 | 0.0191 | 7.0603 | ** |
| 3 | Conjoint and Low frequency | 841.0070 | 0.1260 | 0.0230 | 5.4291 | ** |
| 4 | Conjoint and Nonword | 807.3038 | 0.0847 | 0.0193 | 4.3524 | ** |
| 5 | Crossed and Low frequency | 829.4808 | -0.0328 | 0.0231 | -1.3755 | (ns) |
| 6 | Uncrossed and Low frequency | 930.6656 | -0.0371 | 0.0284 | -1.2622 | (ns) |
| 7 | Crossed and Nonword | 811.4315 | -0.0131 | 0.0189 | -0.6568 | (ns) |
| 8 | Uncrossed and Nonword | 813.9509 | -0.1297 | 0.0220 | -5.8528 | ** |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Target | 287 | 0.0094 | 0.0971 |
| Participant | 36 | 0.0276 | 0.1663 |
| Residuals | | 0.0895 | 0.2991 |

($\mathrm{T} = 7.06$, $p < 0.01$). For low frequency words, line 6 vs. line 3 show model predicted RT of of 927 ms vs. 841 ms for the Uncrossed vs. Conjoint conditions, respectively ($\mathrm{T} = 4.72$, $p < 0.01$; T test not shown). The implication is that the Uncrossed fixation disparity condition is harder than either the Conjoint or the Crossed fixation disparity conditions.

## 4.5 Exp. V. Contralateral and ipsilateral haploscope presentations of conjoint, crossed and uncrossed single words

The reason for this experiment was to verify the findings in Exp. **III** and test to see if the results hold when the stimuli are presented in an ipsilateral manner as well as a contralateral manner.

### 4.5.1 Design, methods and participants

The design for this experiment is as for Exp. **III**, except that it has more word and nonword targets so that I could include ipsilateral versions of the three experiment conditions. I enlarged the target set to include 96 high frequency, 96 low frequency (taken from the MRC database as before), and 24 phonologically regular nonwords. Participants saw equal numbers of all six experiment conditions, namely $\mathrm{Conjoint}_{\mathrm{Contralateral}}$ and $\mathrm{Conjoint}_{\mathrm{Ipsilateral}}$, $\mathrm{Crossed}_{\mathrm{Contralateral}}$ and $\mathrm{Crossed}_{\mathrm{Ipsilateral}}$, and $\mathrm{Uncrossed}_{\mathrm{Contralateral}}$

and $\mathrm{Uncrossed}_{\mathrm{Ipsilateral}}$ (shown to different participants in a Latin Square design). An example of the stimuli for these six experiment condition and their corresponding letters to each hemisphere is shown in Figure 4.7

The Conjoint experiment conditions had three letters completely overlapped between the two eyes relative to the fixation cue, with the contralateral version shown as (tabl_)(_able) and the ipsilateral version shown as (_able)(tabl_). The position of the fixation cue is shown by the highlighted letter ('b' in this case). In the $\mathrm{Crossed}_{\mathrm{Contralateral}}$ and $\mathrm{Crossed}_{\mathrm{Ipsilateral}}$ conditions the letters were arranged with respect to the cue such that the left eye would focus on the space between the third and fourth letters and the right eye would focus on the space between the second and the third letters, giving rise to a one-letter crossed fixation disparity. The difference between these two conditions was in the location of the missing letter for each eye; hence the contralateral version was (tab|l_)(_a|ble), and the ipsilateral version was (_ab|le)(ta|bl_). In the $\mathrm{Uncrossed}_{\mathrm{Contralateral}}$ and $\mathrm{Uncrossed}_{\mathrm{Ipsilateral}}$ experiment conditions, the left eye would focus on the space between the second and the third letters, and the right eye would focus on the space between the third and fourth letters, giving rise to a one-letter uncrossed fixation disparity. As in the previous cases, the difference between these two condition was in the location of the missing letter for each eye; hence the contralateral version was (ta|bl_)(_ab|le), and the ipsilateral version was (_a|ble)(tab|l_).

As before, participants consisted of university students who had learned English at an early age, signed consent forms and were paid for their participation.

### 4.5.2 Results

A total of 46 participants took part (27 females and 19 males; aged from 18 to 36). Figure 4.8 shows the results using the same type of plot as in Fig. 4.2. As can be seen, the data shown contralaterally (left panel) performs similarly to the data shown contralaterally in Exp. **III** (Fig. 4.2), showing again that the Crossed condition is perceived more correctly than the Uncrossed condition (only responses with all five letters correct are plotted). However, the ipsilaterally presented stimuli (the panel on the right in Fig. 4.8) shows a very different pattern, with the Uncrossed conditions being perceived more correctly than the Crossed conditions. The critical difference in the materials resides in the details of the overlapping of stimuli letters with respect to the Crossed and Uncrossed conditions.

In the Uncrossed condition with contralateral presentation, two letters appear on each side of the vertical cue for both eyes; for example, (ta|bl_)(_ab|le). A similar type of overlapping of two letters to each side of the vertical cue happens for the Crossed

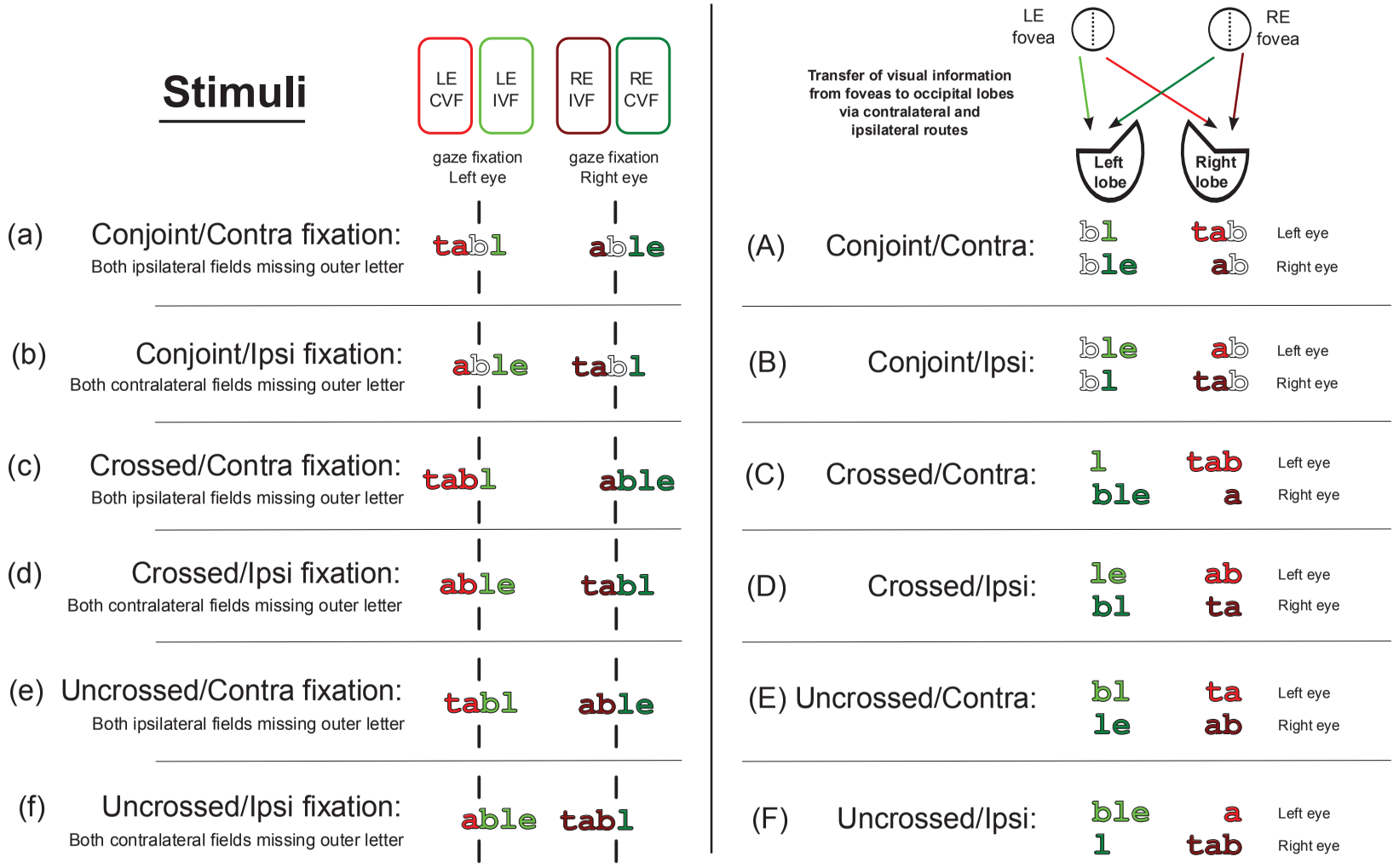


Figure 4.7: Experiment design for Conjoint, Crossed and Uncrossed fixations, under both Contralateral and Ipsilateral presentations.

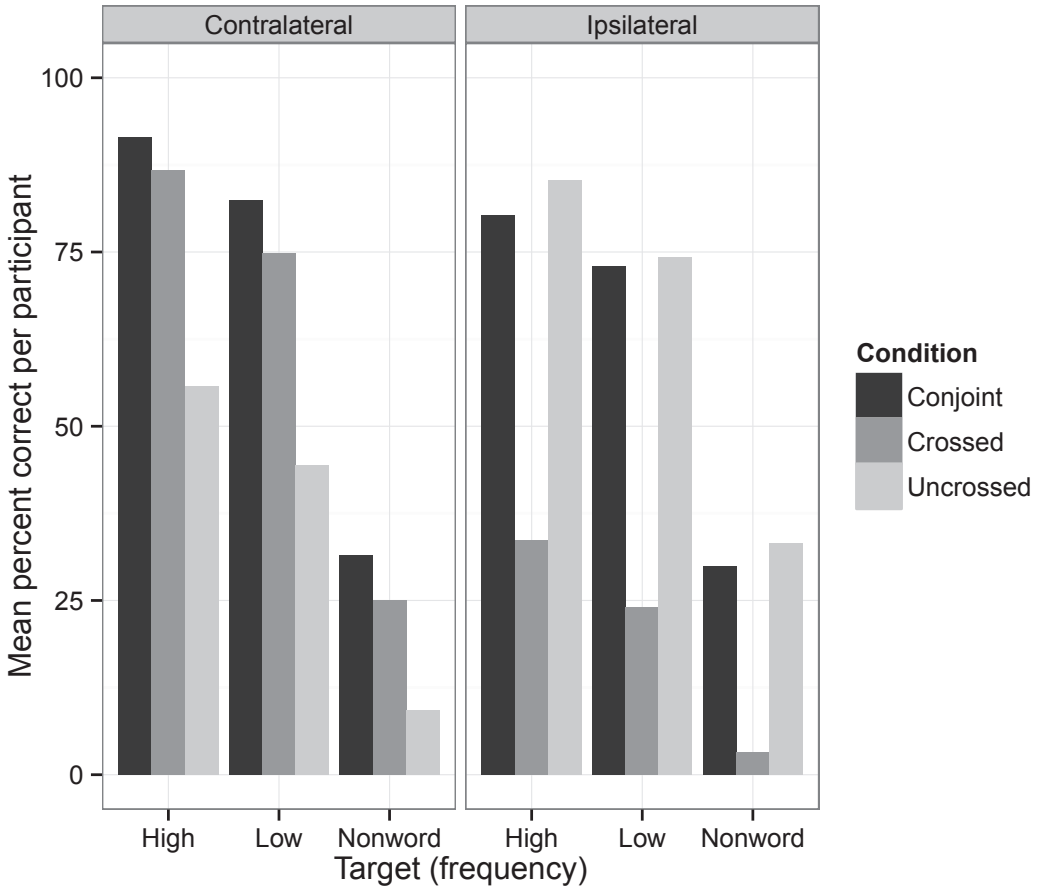


Figure 4.8: Proportion of correct target responses for Conjoint, Crossed and Uncrossed fixation disparity conditions, for words and nonwords, and for contralateral and ipsilateral presentation modes.

condition but with an ipsilateral presentation: (_ab|le)(ta|bl_). I will refer to these cases as "2-2 Overlap".

In the Crossed condition with contralateral presentation, the overlapping of letters in each hemifield is asymmetric; for example, (tab|l_)(_a|ble). In these cases, the left hemifields are presented with stimuli that contain three letters in the LE versus one letter in the RE, and similarly for the right hemifields. The same type of asymmetric letter overlapping happens in the Uncrossed condition with ipsilateral presentation; for example, (_a|ble)(tab|l_). I will refer to these cases as "3-1 Overlap".

In the Conjoint condition, the middle three target letters always coincide in terms of the two eyes; For example, in the contralateral presentation (tabl_)(_able), the letters "abl" occupied the same location in space with respect to the focus of attention in the two eyes (and likewise for the ipsilateral presentation). I will refer to these cases as "Conjoint Overlap".

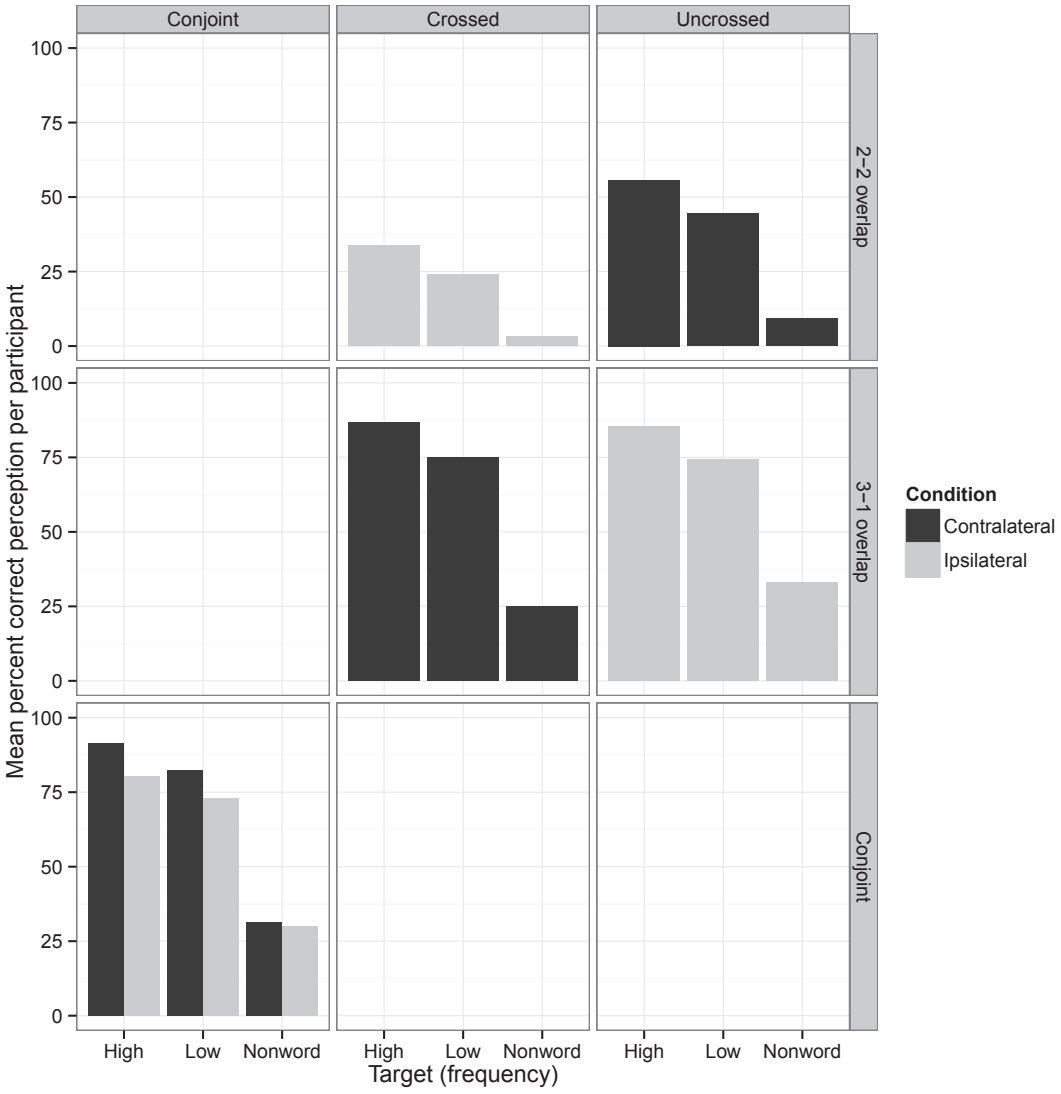


Figure 4.9: Proportion of correct target identification, separated by type of stimuli overlap (Conjoint, 2-2 Overlap, 3-1 Overlap) across the two eyes, experiment condition and presentation method (contralateral or ipsilateral).

Figure 4.9 shows the same data as in Fig. 4.8, but separated into experiment condition and type of overlap. Clearly, while the Conjoint condition contains both contralateral and ipsilateral data, the Crossed and Uncrossed experiment conditions are divided between type of overlap and method of presentation. Consequently, I will show a separate analysis for $(i)$ the conjoint data, and $(ii)$ for the Crossed/Uncrossed vs. 2-2/3-1 overlap of letters.

Note that for this and the following LMER tables I have included the complete within-subject random intercepts per participant, as there were more participants in this experiment as in the previous experiments. This addition to the LMER modelling

process improved the model prediction values and did not change the pattern of the results.

#### 4.5.2.1 Conjoint stimuli: A variation on the $Contralateral > Ipsilateral$ hypothesis in Exp. I

$$
\begin{aligned}
Correct\{0:5\} \sim\ & PresentationCondition\{\text{Contralateral}, \text{Ipsilateral}\} + \\
& TargetFrequency\{\text{High}, \text{Low}, \text{Nonword}\} + \\
& (Presentation + Frequency + ResponseRT \mid Participant) + \\
& (1 \mid Target), \\
& \text{data} = \text{Only conjoint presentations}, \\
& \text{model} = \text{poisson}
\end{aligned} \tag{4.3}
$$

Figure 4.10: LMER model equation for the Conjoint condition with both contralateral and ipsilateral modes of presentation

Table 4.3: LMER model for correct letter identification, for only the Conjoint condition in either contralateral or ipsilateral modes of presentation (Model 4.3).

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Contralateral; High Frequency | 0.4858 | 1.5805 | 0.0148 | 106.6880 | |
| 1 | Ipsilateral | 0.4729 | -0.0269 | 0.0191 | -1.4044 | (ns) |
| 2 | Low Frequency | 0.4757 | -0.0210 | 0.0185 | -1.1357 | (ns) |
| 3 | Nonword | 0.3774 | -0.2524 | 0.0373 | -6.7622 | *** |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Target | 220 | 0.0000 | 0.0000 |
| Participant | 46 | 0.0000 | 0.0000 |
| Ipsilateral/Pp | | 0.0055 | 0.0740 |
| Low Frequency | | 0.0025 | 0.0497 |
| Nonword | | 0.0219 | 0.1479 |
| Response delay/Pp | | 0.0057 | 0.0752 |

The Conjoint data for five letter targets is loosely a replication of Exp. **I**, but with only one letter missing in each eye and no "Both" condition; it can be used to test the hypothesis that contralateral visual fields are preferred over ipsilateral visual fields. As expected, the contralateral mode of presentation produced more numbers of correctly identified letters than the ipsilateral mode of presentation (line 0 vs. line 1 in Table 4.3); Predicted values for correctly reported letters: $Contralateral = 4.92$, $Ispilateral =$

4.72 ($Z-score=-2.76$, $p<0.01$). As seen in Exp. **I**, participants tend to get more letters correct when the stimuli are on the screen for longer periods of time. With 85 ms presentation durations used in the current experiment, the numbers of correctly reported letters are almost at ceiling (five letters), nevertheless, the $Contralateral > Ipsilateral$ finding remains.

Line 2 in Table 4.3 shows that low frequency words are significantly harder to perceive than high frequency words (line 0), $Z-score=-2.25$, $p<0.05$. Furthermore, nonwords (line 3) are even harder to report correctly but nevertheless show a $Contralateral > Ipsilateral$ effect.

#### 4.5.2.2 The asymmetric Overlapping of letters

$$
\begin{aligned}
Correct\{0:5\} \sim\ & PresentationCondition\{\text{Contralateral, Ipsilateral}\} * \\
& ExperimentOverlay\{2-2 \text{ Overlap}, 3-1 \text{ Overlap}\} + \\
& TargetFrequency\{\text{High, Low, Nonword}\} + \\
& (Presentation * Overlay + Frequency + ResponseRT \mid Pp) + \\
& (1 \mid Target), \\
& \text{data} = \text{Non}-\text{conjoint presentations}, \\
& \text{model} = \text{poisson}
\end{aligned}
\tag{4.4}
$$

Figure 4.11: LMER equation for the Crossed and Uncrossed conditions with both contralateral and ipsilateral modes of presentation, resulting in 2-2 and 3-1 Overlaps.

The LMER model in Table 4.4 shows the analysis for numbers of correctly reported letters by the method of presentation (contralateral or ipsilateral) and by type of letter overlap (2-2 vs. 3-1) for non-conjoint overlap cases. As can be seen from Fig. 4.9, the contralateral and ipsilateral presentations are switched between the 2-2 overlap and 3-1 overlap cases and thus correspond to different experiment conditions (Crossed or Uncrossed) over the two letter-overlap cases.

With respect to the 2-2 overlap cases, the contralateral presentation –which is also the Uncrossed condition– leads to significantly more correctly reported letters than the ipsilateral presentation –the Crossed condition– (line 0 vs. line 1 in Table 4.4, Z-score = -2.61, $p<0.01$). The task is harder and the model predictions are lower than for conjoint presentations (Table 4.3), with 4.1 and 3.7 letters for the contralateral and ipsilateral presentations, respectively in the 2-2 overlap cases versus 4.92 and 4.72 in the conjoint cases. Again, the low frequency words and the nonwords are significantly harder to perceive than the high frequency words (lines 3 and 4 in Table 4.4, predicted values for correct letters are 3.81 and 3.17, respectively).

Table 4.4: LMER model for numbers of correct letter identifications, for non-conjoint conditions in either contralateral or ipsilateral modes of presentation and 2-2 Overlap, 3-1 Overlap cases (Model 4.4).

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Contralateral and 2-2 overlap (Uncrossed); High Frequency | 0.3774 | 1.3281 | 0.0310 | 42.8588 | |
| 1 | Ipsilateral and 2-2 overlap (Crossed) | 0.3505 | -0.0739 | 0.0411 | -1.7970 | (.) |
| 2 | Contralateral and 3-1 overlap (Crossed) | 0.4688 | 0.2169 | 0.0251 | 8.6563 | *** |
| 3 | Low Frequency | 0.3572 | -0.0550 | 0.0138 | -3.9876 | *** |
| 4 | Nonword | 0.2819 | -0.2918 | 0.0338 | -8.6320 | *** |
| 5 | Ipsilateral and 3-1 overlap (Uncrossed) | 0.4695 | 0.0755 | 0.0432 | 1.7449 | (.) |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Target | 220 | 0.0000 | 0.0000 |
| Participant | 46 | 0.0388 | 0.1970 |
| Ipsilateral/Pp | | 0.0777 | 0.2787 |
| 3-1 overlap/Pp | | 0.0182 | 0.1349 |
| Low Frequency | | 0.0010 | 0.0314 |
| Nonword | | 0.0307 | 0.1751 |
| Response delay/Pp | | 0.0490 | 0.2214 |
| Ipsilateral:3-1_overlap/Pp | | 0.0735 | 0.2712 |

Table 4.5: LMER model for numbers of correct letter identifications, for non-conjoint conditions. The intercept is assigned to the ipsilateral 3-1 Overlap case (an Uncrossed condition) so that it can be compared directly to the contralateral 3-1 Overlap case (Model 4.5).

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Ipsilateral and 3-1 overlap (Uncrossed); High Frequency | 0.4694 | 1.5463 | 0.0172 | 89.9249 | |
| 1 | Contralateral and 3-1 overlap (Crossed) | 0.4689 | -0.0010 | 0.0166 | -0.0619 | (ns) |
| 2 | Ipsilateral and 2-2 overlap (Uncrossed) | 0.3505 | -0.2920 | 0.0327 | -8.9315 | *** |
| 3 | Low Frequency | 0.4428 | -0.0584 | 0.0138 | -4.2291 | *** |
| 4 | Nonword | 0.3508 | -0.2913 | 0.0338 | -8.6063 | *** |
| 5 | Contralateral and 2-2 overlap (Crossed) | 0.3804 | 0.0827 | 0.0445 | 1.8568 | (.) |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Target | 220 | 0.0000 | 0.0000 |
| Participant | 46 | 0.0047 | 0.0687 |
| Ipsilateral/Pp | | 0.0000 | 0.0038 |
| 3-1 overlap/Pp | | 0.0385 | 0.1961 |
| Low Frequency | | 0.0011 | 0.0332 |
| Nonword | | 0.0308 | 0.1756 |
| Response delay/Pp | | 0.0493 | 0.2220 |
| Ipsilateral:3-1_overlap/Pp | | 0.0761 | 0.2758 |

$$
\begin{aligned}
Correct\{0:5\} \sim\ & PresentationCondition\{\text{Ipsilateral}, \text{Contralateral}\} * \\
& ExperimentOverlay\{3-1 \text{ Overlap}, 2-2 \text{ Overlap}\} + \\
& TargetFrequency\{\text{High}, \text{Low}, \text{Nonword}\} + \\
& (Presentation * Overlay + Frequency + ResponseRT \mid Pp) + \\
& (1 \mid Target), \\
& \text{data} = \text{Non} - \text{conjoint presentations}, \\
& \text{model} = \text{poisson}
\end{aligned} \tag{4.5}
$$

Figure 4.12: LMER equation for the ipsilateral vs. contralateral modes of presentation with both contralateral and ipsilateral modes of presentation, resulting in 2-2 and 3-1 Overlaps.

The two 3-1 overlap cases show a different pattern of results, however. For this analysis I have chosen the Ipsilateral 3-1 overlap case –the Uncrossed condition– as the intercept and contrasted the contralateral presentation to it –the Crossed condition– (Table 4.5); there was no significant difference between the two 3-1 overlap cases, with both the contralateral and ipsilateral modes of presentation predicting about 4.78 letters correct. Furthermore, the level of performance in the 3-1 overlap cases was comparable to the conjoint cases where the model predicted about 4.92 and 4.72 correctly identified letters for the contralateral and ipsilateral conditions, respectively.

While low frequency and nonword targets were reported significantly less correctly than the high frequency targets (lines 3 and 4 vs line 0 in Table 4.5), the predicted numbers of correctly identified letters of 4.46 and 3.71 were higher than the 2-2 overlap cases (3.81 and 3.17, respectively), again showing that the 3-1 overlap cases were easier for the participants than the 2-2 overlap cases.

#### 4.5.2.3 Other findings

Eye separation (distance between centres of pupils, spanning from 54 to 66 cm) did not explain any variance when added into the LMER models for either conjoint or non-conjoint overlap cases, neither separately nor as an interaction with overlap or experiment condition. While Sex did not explain any significant variance in this experiment, it was not well balanced (27 females and 19 males).

## 4.6 Chapter conclusions

The three experiments in this chapter have been carried out to address the question of why we would employ non-conjoint fixations in reading with two eyes. The haploscope was used so that both eyes were needed to see all the letters in the target, which consisted of five letters (chosen from high frequency words, low frequency words and non-words),

where each eye was shown only four of the five letters. The three experiment conditions were $(i)$ conjoint fixation, $(ii)$ one letter crossed fixation disparity, and $(iii)$ one letter uncrossed fixation disparity.

While the first experiment (Exp. **III**) recorded letters reported by the participant in a challenging perceptual task, the second experiment (Exp. **IV**) recorded RT and correct categorisation in a classical lexical decision task. Both experiments presented the stimuli in a contralateral manner (where the missing fifth letter was in the ipsilateral visual field) for 85 ms. Exp. **III** found that the Uncrossed condition was significantly less correctly reported, with the Crossed condition non-significantly distinguished from the Conjoint condition. Exp. **IV** found that while the Conjoint, Crossed words and nonwords were correctly categorised at above-chance levels, the Uncrossed words (but not the non-words) were categorised at chance levels. Furthermore, the Uncrossed words were responded to in a significantly longer time than the Conjoint or Crossed words.

However, the Crossed and Uncrossed conditions presented the foveal hemifields with different numbers of letters. In an attempt to correct for this inbalance, Exp. **V** added ipsilateral presentations of the stimuli (where the missing fifth letter was in the contralateral visual field) to the challenging perception task (Exp. **III**). This third experiment found that, while the contralaterally presented stimuli were responded to in a similar manner to the contralaterally presented material in Exp. **III**, the ipsilaterally presented stimuli show an opposite pattern of responses for the Crossed and Uncrossed conditions. Reinterpreting the stimuli in terms of visual saliency across the four hemifoveal fields provided a clue as to what was occurring in the response patterns.

On the one hand, the Conjoint fixations always contained the same centre three letters overlapped in space. The difference between the contralateral and ipsilateral presentations of Conjoint fixations showed that the contralaterally presented stimuli were significantly more correctly perceived than the ipsilaterally presented stimuli, providing a replication for Exp. **I**.

On the other hand, the Crossed and Uncrossed conditions were separated by the complexity of the overlapping of the stimuli in each hemifield. That is, the contralaterally presented Uncrossed condition and the ipsilaterally presented Crossed condition both presented exactly two letters in each hemifovea, with these letters shifted by one across the two eyes (referred to as "2-2 overlap"); for example, (`ta|bl_`)(`_ab|le`) and (`_ab|le`)(`ta|bl_`) respectively. Exp. **V** showed that these cases were harder than the Conjoint cases, with the contralaterally presented Uncrossed condition being perceived significantly more accurately than the ipsilaterally presented Crossed condition. It remains unclear whether the difference between these two conditions is due to a $contralateral > ipsilateral$ effect, an advantage afforded by the Uncrossed condition

projecting the stimuli to appear within the horopter (Shillcock et al., 2010), or both explanations together.

In contrast, the ipsilaterally presented Uncrossed condition and the contralaterally presented Crossed condition presented each hemifield with an asymmetrical distribution of letters. That is, each hemifield contained three letters from one eye and one letter from the other eye (referred to as "3-1 overlap"); for example, (_a|ble)(tab|l_) and (tab|l_)(_a|ble) respectively. An analysis of these two cases showed that they were being equally correctly perceived and on the same level of accuracy as the conjointly presented material.

Interestingly, in the latter two cases all the five letters were presented to either the contralateral or ipsilateral visual fields and the single letter in each hemifield did not provide any new information for resolving the target. This is in contrast to the former two cases where both contralateral and ipsilateral visual fields contained letters that were not in the other ipsilateral or contralateral visual fields. In other words, the 2-2 overlap cases necessitated both contralaterally and ipsilaterally presented letters but the 3-1 overlap cases only required contralateral or ipsilateral visual fields. In light of the results from the Many/Few beginnings and endings six letter experiment (Exp. **VI**), perhaps the 3-1 overlap cases –together with the conjoint cases– allow for each cerebral hemisphere to carry out its unique task by utilising only input from one eye. The 2-2 overlap cases however require each cerebral hemisphere to utilise visual information from both eyes and therefore has to successfully resolve the overlapping of the two letters to be able to carry out its role in visual perception of the letters.

In all cases, the pattern of results showed that the correct perception of the letters was mediated by statistical exposure to written text: high frequency words were most correctly perceived, followed by the low frequency words and lastly by nonwords. Furthermore, a single horizontal shift of the stimuli by half a letter in each eye (equating to one letter of difference across the two eyes) was enough to trigger large differences in both visual perception and lexical decision, again showing direct behavioural evidence for a vertical foveal splitting of the stimuli.

The experiments in this chapter have provided a rich cross-section of data that can be used for modelling separate hemispheric effects stemming from the vertical division of words. I will follow this up in Chapter 6, where I outline a proposal for a computational model for word perception that incorporates the notion of two hemispheres operating separately and cooperatively on separate sublexical forms to arrive at the target word.

One conclusion that can be projected forward from these data is that the eyes do not have to focus on the same position in text to be able to resolve non-identical sublexical tokens into target words. When the overlapping of letters is identical (i.e., conjoint

fixations), or when there is little competition between the letters arriving initially to each hemisphere (the 3-1 overlap cases), the processor is operating maximally.

However, in the 2-2 overlap cases where the two letters on each side of the fixation cue are different in each eye, the processor has a more difficult task (as measured by correct letter responses). And, while there is a significant difference between crossed and uncrossed fixation disparities (favouring the uncrossed), the latter condition also happened to be contralaterally based. Thus, it is unclear whether the effect seen in the 2-2 overlap cases is due to uncrossed versus crossed fixation disparity, or due to contralateral versus ipsilateral word differences in the stimulus.

# Chapter 5

# Effects of word beginning and ending neighbourhood sizes

## 5.1 Chapter overview

In this chapter I use the haploscope to explore how target word beginning and ending sub-lexical components contribute to visual word perception. According to SFT, letter sequences falling on to the left and right sides of the fovea would be projected to right and left hemispheres respectively. I test the hypothesis that this vertical division of visual input affords a hemispheric advantage by allowing each hemisphere to process the letters that arrive to the corresponding foveal areas. This would further strengthen the claim for a vertically split fovea by showing processing differences that are less likely to be mediated solely by ganglion/cone foveal density or by lexicon statistics, but rather by hemispheric processing propensities.

Experiment **VI** uses the same paradigm as Exp. **I** of showing half-words (from six-letter targets) to each eye so that the visual input from both eyes is needed to correctly perceive the intended target. Experiment conditions are made up of both contralaterally and ipsilaterally presented stimuli to ensure the lateralisation of the stimuli.

## 5.2 Sublexical effects: Hemispheric processing propensities

In assuming a vertically split fovea for each eye and the consequent splitting of the foveated word, I explore the outcomes of providing the two hemispheres with different sublexical strings that, when concatenated in a conjoint manner across the two eyes, make a word. As before, the cognitive task at hand was one of perceiving a single word from the separate half-word letter strings shown to each eye.

Besides the current literature available on different hemispheric effects (mostly visual half-field experiments that however did not include foveal stimulation, but see especially Lavidor et al., 2004; Perea, Acha, and Fraga, 2008), my motivation for carrying out this experiment came from the four-letter Both/Contralateral/Ipsilateral experiments (Chapter 3) where I found a tendency for the beginning and ending bigrams to influence

correctness of response. However, these were post-hoc analyses and the beginning and ending bigram frequencies were not controlled.

As the beginning and ending bigrams in four-letter words do not allow for a well-distributed partitioning of words into many and few beginning and ending neighbourhoods, I chose to carry out this experiment with six letter words which do have many more sequences for beginning and ending sub-strings that are more evenly distributed between high and low neighbourhood type-count frequencies.

## 5.3 Hypothesis

For most people, years of structured education with a strong demand on reading abilities has dovetailed with inherent processing abilities of the two cerebral hemispheres, so as to carry out the task of word identification in an optimised and accurate manner.

The hypothesis I test in this chapter is that each hemisphere contributes in a separate but complementary way to this task. Specifically, the question at hand is, How do the hemispheres function when given sublexical strings with different neighbourhood sizes (defined as n-gram type-count frequencies)?

As most eye fixations typically fall somewhere within words, the ends of words (in the RVF) would be initially projected to the LH and the beginnings of words (in the LVF) would be projected to the RH. Thus, the RH would specialise in the beginnings of words and the LH would specialise in the ends of words. Importantly, each hemisphere would carry out a separate strategy so as to achieve an optimum functionality. My proposal for this dual optimised strategy, given what is known about hemispheric specialisation, is that the RH/LVF would contribute with coarse-grain processing, and the LH/RVF would contribute with fine-grain processing. That is, larger sublexical neighbourhood sizes for word beginnings would increase the RH processor's ability to recognise words –a coarse-grain effect–. Also, smaller sublexical neighbourhood sizes for word endings would increase the LH processor's ability to recognise words –a fine-grain effect.

Furthermore, considering what I found in Chapter 3 where contralaterally presented letters are reported more correctly than ipsilaterally presented letters, a contralateral presentation of half-word stimuli would boost this effect over an ipsilateral presentation of the same stimuli.

## 5.4 Exp. VI. Hemispheric effects in contralateral and ipsilateral single word perception

### 5.4.1 Paradigm

I used the timed haploscope experimental paradigm described in chapter 3 that gives me the ability to project exclusively to contralateral or ipsilateral visual fields. The

dependent measure is number of correctly named letters. For this to be challenging and yet allow participants to perceive single words when presented with just half-words to each eye, I gave a pretest to each participant where I presented a separate set of 24 stimuli arranged as in the experiment, but at two different presentation durations to see at which duration they managed to make correct responses as well as make erroneous responses.

#### 5.4.1.1 Contralateral and Ipsilateral presentations

If I display a centrally fixated target to both eyes simultaneously, I cannot know which part of the displayed text is arriving to which hemisphere (or indeed, whether this visual information is duplicated from each eye), as the LVF is arriving through two avenues to the RH, as well as the RVF arriving arriving to the LH through contralateral and ipsilateral avenues. Furthermore, if I display centrally fixated text to just one eye, one part of the target will have a preferred treatment over the other half of the target. So as to avoid these ambiguous possibilities, I chose to present targets in exclusively $(i)$ Contralateral, or $(ii)$ Ipsilateral presentations. Thus, I have two known sources of variability that I manipulate through experimental design: $(1)$ $\mathrm{Contralateral} > \mathrm{Ipsilateral}$, and $(2)$ different N-gram type-count neighbourhood preferences between the hemispheres. The variable I want to explore in this experiment is the importance of neighbourhood sizes for beginning and ending n-grams.

### 5.4.2 Methods

#### 5.4.2.1 Participants

As before, I found that different people needed different stimulus presentation durations to perform with errors but not too many errors. In an effort to achieve similar numbers of male and female participants, I tested 42 native English speaking university students (who had grown up speaking English as their principal language). All participants signed an informed consent form and were paid for their time.

#### 5.4.2.2 Stimuli

**The British National Corpus (BNC).** It is very important that the manner of calculating the n-gram neighbourhood sizes reflects the probability of exposure to them (in a similar way that word usage frequency counts facilitate my capabilities of correctly recognising the target). The MRC corpus that I have been using to generate my materials for the previous experiments is based on a small corpus of words (150,837 word entries) relative to the more recent corpora. The newer and larger corpora better represent the many alternative representations of the possible beginning and ending n-grams. Given that I am testing native English speakers in the UK, I decided to use the

British National Corpus (100 million words collected from samples of written and spoken language, The BNC Consortium (2007)) to generate the stimuli for this experiment.[1]

The BNC however has not been purged of errors and other extraneous letter strings that appear in normal text. So, unlike the MRC corpus where I expect that all the entries are valid words, I had to use a minimum occurrence cut-off to make sure that I was picking up (mostly) valid words. Roberts and Chater (2008) found that a minimum cut-off of 50 occurrences/million produced a statistically representative selection of valid word strings that are likely to occur in print.

Furthermore, capitalised and lower-case words in the BNC are collapsed into the same label. Whereas there is a fine-coding of word categories, this is often unclear as to what is a capital usage of the word. This is important because the capital letters have a different visual presentation and hence a different range of frequencies of visual occurrences than lower-case letters.

**Type-count neighbours** For this experiment I used six-letter words chosen from a complete spectrum of the British National Corpus (BNC) of written word frequencies. I chose a larger six-letter word size so as to reduce the possibility of guessing the target word because there are simply more of them than four-letter words. Furthermore, with the larger number of possible five- six- and seven-letter words, choosing six letter target words also allows me to fully manipulate many and few token count neighbourhood sizes.

I explored five through seven letter words from both the BNC written corpus(Kilgarriff, 1997, downloaded 23-Oct-2008 from `www.kilgarriff.co.uk/bnc-readme.html`) and the MRC corpus (Kučera and Francis, 1967; Wilson, 1988). I chose to include the five and seven letter words because in my haploscope trials I found that people are not always aware of how long the target word should be. I found that there were a significant number of five and seven letter responses to the four-letter word targets. Consequently, I used five, six and seven letter words to generate n-gram beginnings and endings candidates for the beginning and ending halves of six letter words.

First, I found that the MRC corpus uses many American spellings and is smaller than the BNC data-set (MRC: 7385, BNC: 16911). Furthermore, the frequency distributions of the words in these two databases are quite different; the MRC data-set is missing a range of medium-to-high words (see Fig. 5.1). The BNC word frequencies on the other hand are more evenly distributed (Fig. 5.2).

**Words used for beginning and ending neighbours** Roberts and Chater (2008) found that university students performed at chance level in deciding whether words in

[1]Data cited herein have been extracted from the British National Corpus, distributed by Oxford University Computing Services on behalf of the BNC Consortium. All rights in the texts cited are reserved.

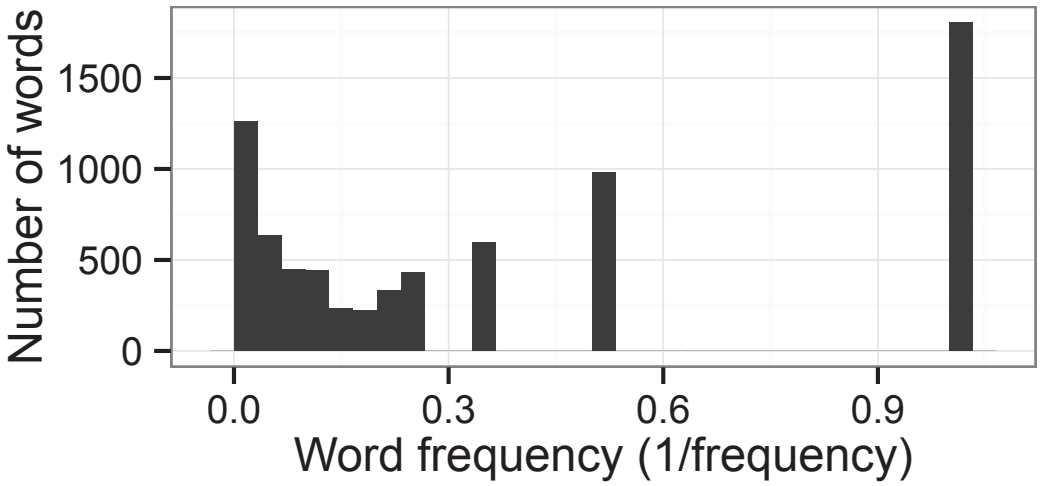


Figure 5.1: Frequency distribution for 5, 6 and 7 letter words in the MRC corpus

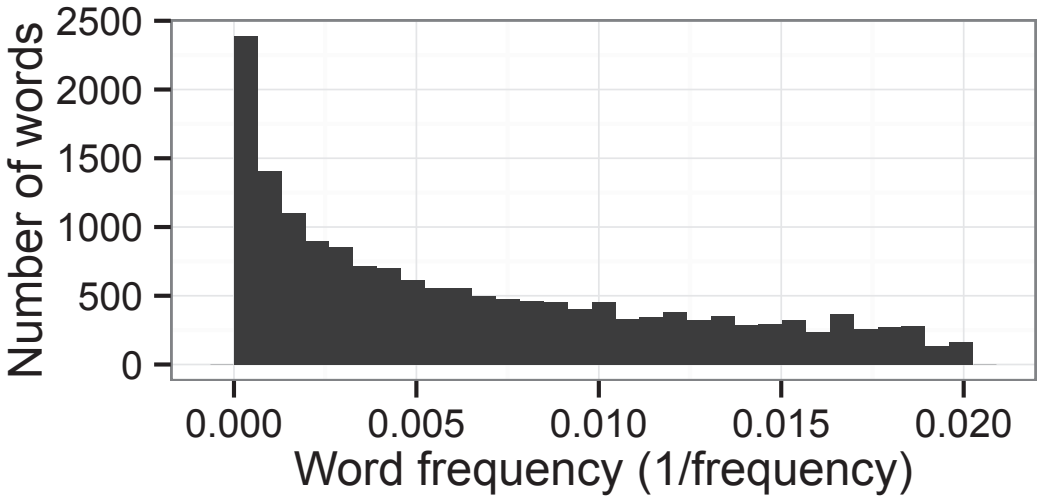


Figure 5.2: Frequency distribution for 5, 6 and 7 letter words in the BNC corpus

the BNC with raw frequency counts up to 50 were non-words. Consequently, I chose to eliminate all BNC words with total raw counts less than or equal to 50 from the BNC data-set. This final list of five through seven letter words constituted the set I used to derive beginning and ending neighbours.

I removed BNC six letter words that had "np0" as part of their type classification (which included proper names); after reviewing the list and keeping words like "fields". The BNC also contains words that would be improper to use as targets (like "asians", "autumn" or "whores"). Consequently I removed these from the list of target words,

but kept them in the list of words used to generate the beginning and ending type-count frequencies.

**Binning the words into MANY and FEW beginning and ending type-count neighbourhoods** The next step in finding the six letter words for my experiments was to classify each word according to its beginning and ending type neighbourhoods. This is more complicated, as it is not clear just what "type neighbourhood" means. Lavidor et al. (2004) used a straightforward count of how many other six letter words shared the same three first or last letters. However, another analysis was used here, stemming from post-hoc analyses on my haploscope experiments, and also the complementary roles of the two hemispheres: each hemisphere contributes in an additive manner to the identification of a word. More specifically, whereas the left hemisphere does well with more unique sequences, the right hemisphere does well when there are several possible candidates (more activations). A simple three-letter token would not do for both of these cases, as a sequence of three letters is more unique than just a single letter (or two letters).

Consequently, I devised a new method of categorising word beginnings and endings into MANY or FEW type neighbourhoods. I decided to use a composite score, shown in Equation 5.1 and 5.2:

$$begin\,score\,(word) = \frac{\mathrm{L1}^{\mathrm{word}}}{\sum \mathrm{L1}} + \frac{\mathrm{L12}^{\mathrm{word}}}{\sum \mathrm{L12}} + \frac{\mathrm{L123}^{\mathrm{word}}}{\sum \mathrm{L123}} \tag{5.1}$$

$$end\,score\,(word) = \frac{{}^{\mathrm{word}}\mathrm{L456}}{\sum \mathrm{L456}} + \frac{{}^{\mathrm{word}}\mathrm{L56}}{\sum \mathrm{L56}} + \frac{{}^{\mathrm{word}}\mathrm{L6}}{\sum \mathrm{L6}} \tag{5.2}$$

Where,

$$\begin{aligned}
\mathrm{L1}^{\mathrm{word}} &= \mathrm{count\,of\,words\,with\,same\,first\,letter} \\
\mathrm{L12}^{\mathrm{word}} &= \mathrm{count\,of\,words\,with\,same\,first\,two\,letters} \\
\mathrm{L123}^{\mathrm{word}} &= \mathrm{count\,of\,words\,with\,same\,first\,three\,letters} \\
{}^{\mathrm{word}}\mathrm{L6} &= \mathrm{count\,of\,words\,with\,same\,last\,letter} \\
{}^{\mathrm{word}}\mathrm{L56} &= \mathrm{count\,of\,words\,with\,same\,last\,two\,letters} \\
{}^{\mathrm{word}}\mathrm{L456} &= \mathrm{count\,of\,words\,with\,same\,last\,three\,letters}
\end{aligned}$$

The principle is as follows: whereas a single letter is the least informative, the end letters are visually salient and hence informative (letters $\mathrm{L1}$ and $\mathrm{L6}$). Three letters together have relatively little chance of occurring frequently, and thus are also very informative (letters $\mathrm{L123}$ and $\mathrm{L456}$). And, two letters tend to resolve easily into a

simple phonetic construct, and hence are also informative. I chose the outer two letters as these will also be most readily accessible from a saliency point-of-view (letters $\mathrm{L12}$ and $\mathrm{L56}$). I then added together these token counts by applying the notion of adding nuggets of informativeness. For the counting procedure I used the complete set of five, six and seven letter words in the BNC (chosen as above). Since the number of occurrences of these letter sequences are cardinally different across the one, two or three cases, I normalised each by dividing the total number of counts for each grouping ($\sum \mathrm{L}\ldots$). The result of this procedure is that each six letter word has a $BeginScore$ and an $EndScore$. For the purpose of ensuring that I obtained an even distribution of target words across both $BeginScore$ and $EndScore$ together, I used a 5x5 matrix of bins to categorise these scores, and then chose 8 target words from each of these 25 bins, giving me a total of 200 target words.

The frequency distributions of the six letter words in these bins are shown in Figure 5.3 for the full BNC data-set. Clearly, this method of deriving a composite value for the Begin and End neighbours does not introduce any bias in terms of frequencies of the words in these bins.

#### 5.4.2.3 Statistical design

I modelled the behavioural data with Liner Mixed Effects regression analyses (LMER), as in Chapter 3. In considering that the analysis of the partially correct data offered a more complete treatment of the data that fortified the correct $\mathrm{vs.}$ incorrect analysis, for the analyses in this chapter I am using all partially correct responses as well as completely correct responses. This implies that the data are modelled with a Poisson count of correct letters distribution as opposed to a logistic distribution for the probability of correct responses.

#### 5.4.2.4 Procedure

The experimental paradigm was similar to the one in the four letter Both/Contralateral/-Ipsilateral haploscope experiment (Chapter 3), except that I only used Contralateral and Ipsilateral presentations of targets (see Figure 5.4). I showed single six-letter words as two three-letter strings to either nasal (i.e., Contralateral) or temporal (i.e., Ipsilateral) hemifoveae, back-masked and for very short durations. The experimental procedure and data collection remained the same as in Experiment **I**. As before, the dependent variable was the participant's response to the question, "Tell me what you felt you saw" to each trial. I immediately typed their reply into the E-prime program that was controlling the experiment.

As the targets were longer than in Experiment **I**, I used a faster screen refresh rate of 84.321 Hz to allow for more flexibility in target presentation durations. I tested different viewing durations to determine what refresh rates I should use, and I found that people

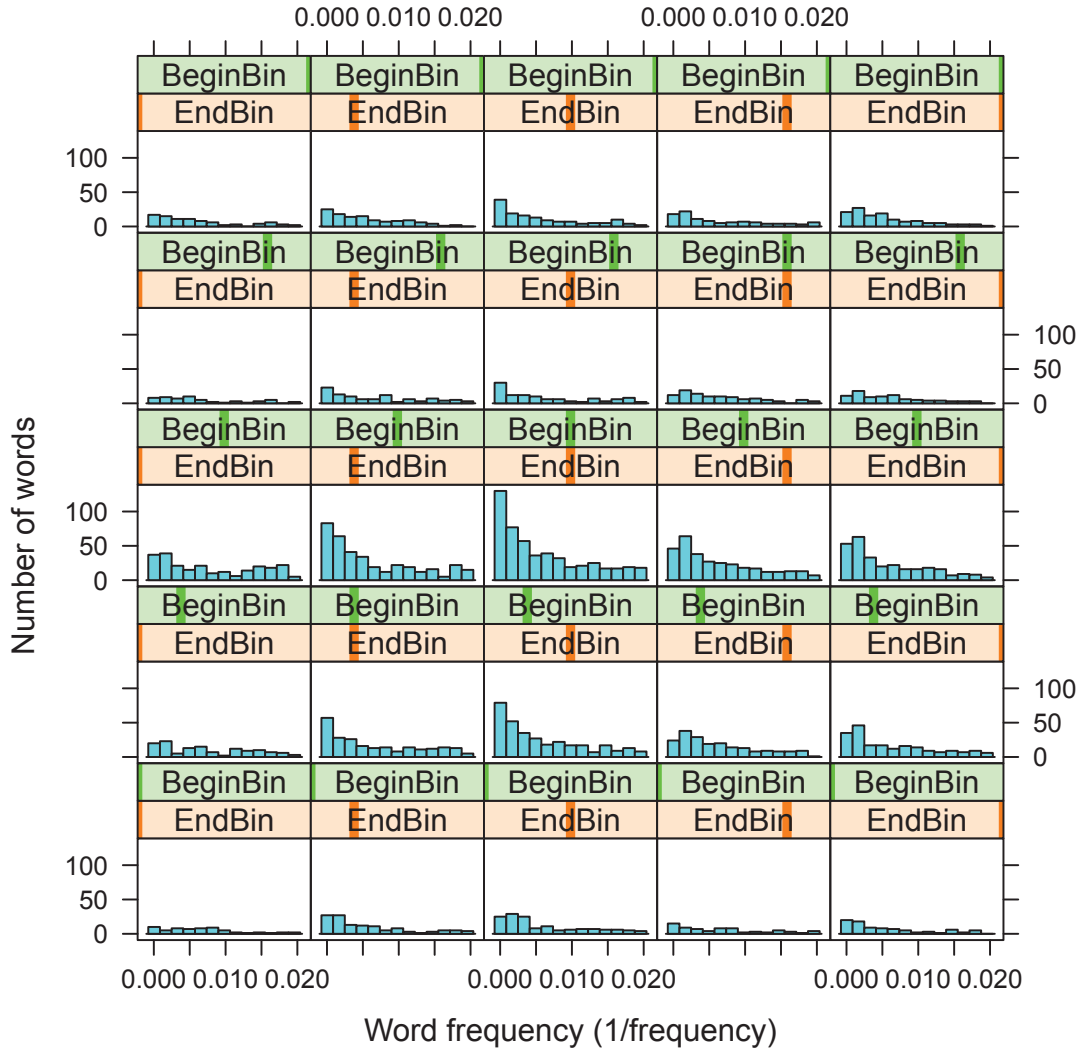


Figure 5.3: Binned word frequencies for all 4318 BNC 6-letter words. Note how each cell contains a distribution of words that reflects the overall tendency seen in Figure 5.2.

needed more time. I found that the shortest durations with satisfactory performance was 36 ms (3 screen refreshes), and that a large group of people needed 83 ms (7 screen refreshes); henceforth I adjusted the experiment to be shown at one of 3 screen refreshes.

As in Experiment **I**, I administered a pre-test where participants were given 16 trials consisting of Contralateral and Ipsilateral conditions and with 47 or 71 ms presentation durations. If they managed to get all trials correct, I administered the experiment with 36 ms durations. If, on the other hand, they hardly managed to get any correct, I administered the experiment with 83 ms durations. If they performed poorly on the 47 ms trials but well on the 71 ms trials, I ran the experiment with 59 ms durations. Finally, if they performed satisfactorily at either the 47 ms or the 71 ms duration,

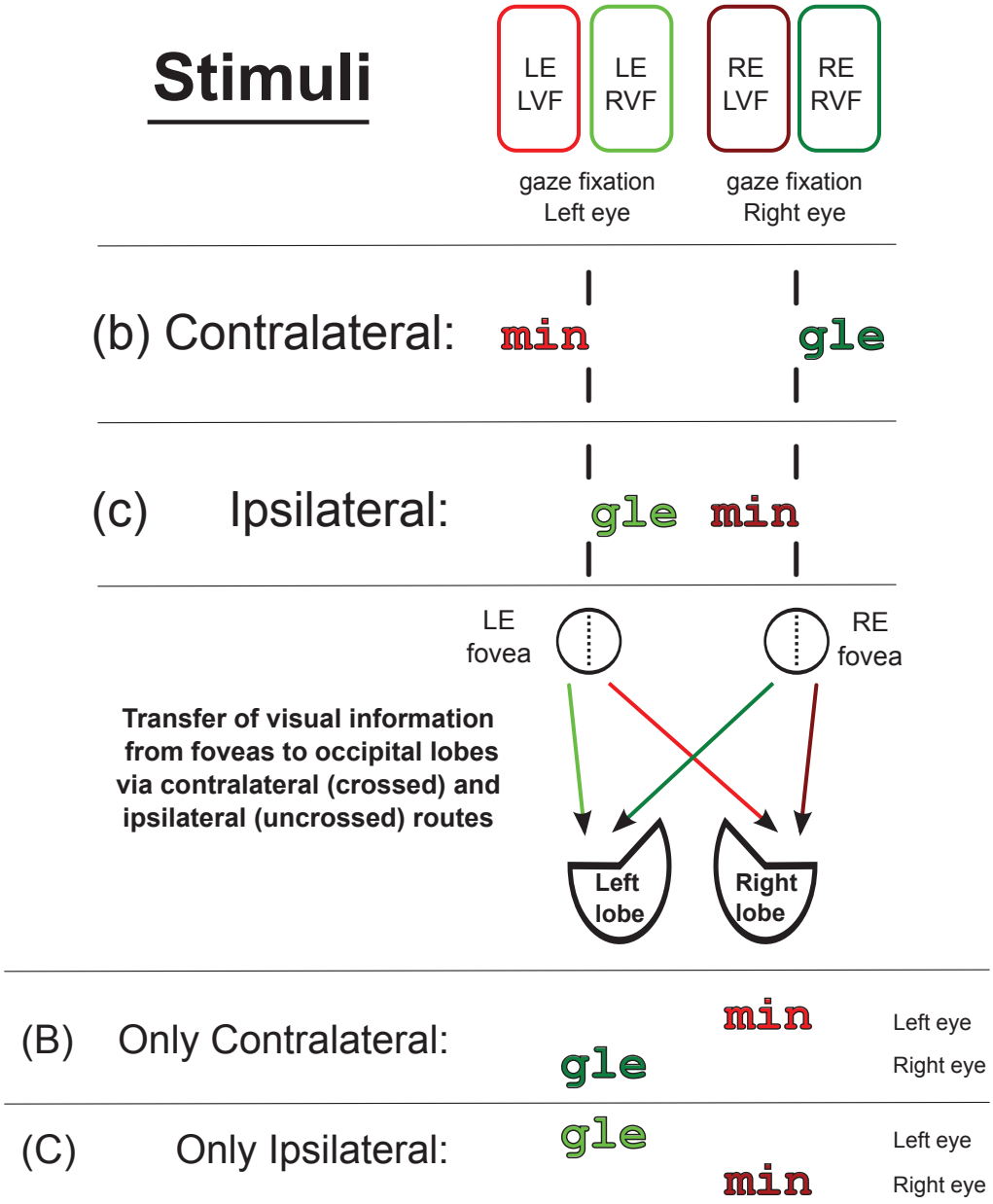


Figure 5.4: Experiment conditions for Many/few Beginning and Ending sublexical neighbours. Only contralateral and ipsilateral conjoint viewing conditions were used.

then I used this optimal duration for the ensuing experiment. All participants were administered the same pre-test trials and in the same order.

After quickly scoring the pre-test I proceeded to run the main experiment with the selected trial presentation durations. Since there were 200 trials, the experiment was broken into five sections of 40 trials each. Targets were randomised within their respective section.

After completing the Haploscope experiment, I gave a handedness test that included four eye preference questions: the moving-head test (described in Experiment **I**); which

eye to a telescope/keyhole question; the Miles test (also known as the Dolman method or the hole-in-the-card test); and a near-point convergence test.

### 5.4.3 Results

#### 5.4.3.1 Participant pool

Out of a total of 42 native English speaking university students who took part in the experiment, 3 could not see a target word from the two half words, and 1 participant needed a presentation duration of more than 83 ms to be able to see a target word.

Consequently, there are 38 (21 females and 17 males) included in the analyses that follows. Their age range is 18 to 37, with a mean of 24.7 years old.

Table 5.1 shows the break-down of presentation durations for these participants.

Table 5.1: Number of participants per trial presentation duration

| Sex | Presentation duration | N |
|---|---|---|
| Female | 36ms | 1 |
| Male | 36ms | 4 |
| Male | 47ms | 1 |
| Female | 59ms | 3 |
| Male | 59ms | 1 |
| Female | 71ms | 5 |
| Male | 71ms | 2 |
| Female | 83ms | 12 |
| Male | 83ms | 9 |

#### 5.4.3.2 The base model

I first looked for variables that are not part of my experimental manipulation, but which do explain a significant portion of the variance of the dependent variable, namely, the number of correctly identified letters (range 0 to 6) in this perception task. I refer to this first model as the base model, expressed as an LMER Table 5.2 with Equation 5.3. It includes: Whether the syllable boundary in the target word falls in the middle of the word (intercept, line 0) or elsewhere (line 1); whether the target is singular (included in the intercept, line 0) or plural (a plural word that ends in 's', line 2); handedness quotient (line 3); the frequency of the target word using the BNC written word frequency (line 4); and the Subtitle word frequency (Brysbaert and New, 2009) for the target word (line 5). All these independent variables significantly explained ($p < 0.001$) a portion of the variance in the modelled number of correct letters.

Since the Subtitle word frequency covaries strongly with BNC word frequency, I only used the residuals of the Subtitle frequency (which also turned out to be significant, Z-score=22.02, $p < 0.001$) that were not explained by the BNC frequency in a separate linear model. The continuous variables ($HQ$, $\log(BNCFreq)$, $\text{residual}(\log(SbtlFreq))$) were all recentred on zero.

Interestingly, participants frequently failed to identify the ending 's' in plural words, and thus plural words obtained a lower number of predicted correct letters (3.71 $\text{vs.}$ non-plural words, 3.85). Handedness Quotient ($HQ$) had a large Standard Error compared to the other variables, implying that this variable was probably not well distributed the participant pool.

Table 5.2: LMER base model statistics (Equation 5.3)

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Syll.Brk=Mid; Singular | 3.9790 | 3.6836 | 0.0573 | 64.2694 | |
| 1 | Syll.Brk!=Mid | 3.8994 | -0.0202 | 0.0047 | -4.2826 | *** |
| 2 | Plural | 3.8421 | -0.0350 | 0.0050 | -6.9365 | *** |
| 3 | HQ | 5.9712 | 0.4059 | 0.1159 | 3.5033 | *** |
| 4 | log(BNCFreq) | 4.1199 | 0.0348 | 0.0012 | 29.4767 | *** |
| 5 | res(log(SbtlFreq)) | 4.1194 | 0.0347 | 0.0017 | 20.6736 | *** |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Participant | 37 | 0.2046 | 0.4523 |
| NxtPrDel\|Pp | | 0.0005 | 0.0222 |

$$
\begin{aligned}
Correct(0-6) \;\sim\; & SyllableBreak\{\text{Middle}, \text{Elsewhere}\} \;+ \\
& Plural\{\text{no}, \text{yes}\} \;+ \\
& HandednessQuotient \;+ \\
& \log(BNCFrequency) \;+ \\
& residuals\left(\log(SubtitleFreq) \sim \log(BNCFreq)\right) \;+ \\
& \left(\sqrt{NextPressDelay} \mid Participant\right), \\
& \text{model} \;=\; \text{Poisson}
\end{aligned}
\tag{5.3}
$$

Figure 5.5: Base model equation

#### 5.4.3.3 Main effects from Contralateral vs. Ipsilateral experiment conditions

The following analysis tested the experiment manipulation of contralateral vs. ipsilateral presentation of half-words. I started with the base model (LMER Table 5.2) and added experiment condition. The result of the statistical modelling can be seen in the LMER Table 5.3 with Equation 5.4, where I contrasted the ipsilateral presentation (line 1) to the contralateral presentation (included in the intercept, line 0).

$$\begin{aligned} Correct(0-6) \;\sim\; & Condition\{\text{Contralateral}, \text{Ipsilateral}\} \;+ \\ & SyllableBreak\{\text{Middle}, \text{Elsewhere}\} \;+ \\ & Plural\{\text{no}, \text{yes}\} \;+ \\ & HandednessQuotient \;+ \\ & \log(BNCFrequency) \;+ \\ & residuals\,(\log(SubtitleFreq) \sim \log(BNCFreq)) \;+ \\ & \left(\sqrt{NextPressDelay} \mid Participant\right), \\ & \text{model} \;=\; \text{Poisson} \end{aligned} \tag{5.4}$$

Figure 5.6: Model equation for Contralateral vs. Ipsilateral main effects

As can be seen, there were significantly more correct letters reported in contralateral presentations than in ipsilateral presentations. Specifically, the model prediction for contralateral correct = 4.005, while the model prediction for ipsilateral correct = 3.952; a Z-score comparison of these two conditions showed them to be different with $p < 0.001$. While these two predicted correct values are significantly different, their values are not very different, as in the results I found in Experiment **I** (Chapter 3). I will address this later.

The remaining fixed effect terms from the base model, namely syllable break in the middle of the word, singular vs. plural, $HQ$ and the two word frequency measures, continued to have separate and significant contributions in explaining the overall variance in the LMER model. I will address these contributions later.

#### 5.4.3.4 Main effects from Beginning and Ending sublexical neighbourhood sizes

The sublexical neighbourhood counts for target beginnings and endings were binned into "Many" or "Few" on the mean scores for the beginning and ending neighbourhood sizes. Thus, I generated a classification for each target word of either "Many-Many", "Many-Few", "Few-Many" or "Few-Few". Table 5.4 shows the LMER statistical model with this categorical variable added to the base model (5.2).

Table 5.3: LMER statistics for the main effects Contralateral vs. Ipsilateral experiment conditions (Equation 5.4)

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Contralateral; Syll.Brk=Mid; Singular | 4.0049 | 3.6901 | 0.0573 | 64.4017 | |
| 1 | Ipsilateral | 3.9524 | -0.0132 | 0.0040 | -3.3154 | *** |
| 2 | Syll.Brk!=Mid | 3.9247 | -0.0202 | 0.0047 | -4.2868 | *** |
| 3 | Plural | 3.8670 | -0.0350 | 0.0050 | -6.9391 | *** |
| 4 | HQ | 6.0096 | 0.4058 | 0.1158 | 3.5056 | *** |
| 5 | log(BNCFreq) | 4.1465 | 0.0347 | 0.0012 | 29.4280 | *** |
| 6 | res(log(SbtlFreq)) | 4.1465 | 0.0347 | 0.0017 | 20.7125 | *** |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Participant | 37 | 0.2045 | 0.4522 |
| NxtPrDel\|Pp | | 0.0005 | 0.0222 |

Table 5.4: LMER Model statistics for beginning and ending Many vs. Few sublexical neighbourhood sizes (Equation 5.5)

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Many-Few; Syll.Brk=Mid; Singular | 4.0370 | 3.6981 | 0.0574 | 64.3790 | |
| 1 | Few-Few | 3.9070 | -0.0327 | 0.0057 | -5.7438 | *** |
| 2 | Few-Many | 3.8550 | -0.0461 | 0.0062 | -7.4035 | *** |
| 3 | Many-Many | 4.0422 | 0.0013 | 0.0066 | 0.1966 | (ns) |
| 4 | Syll.Brk!=Mid | 3.9976 | -0.0098 | 0.0049 | -1.9866 | * |
| 5 | Plural | 3.8690 | -0.0425 | 0.0060 | -7.1341 | *** |
| 6 | HQ | 6.0640 | 0.4069 | 0.1160 | 3.5075 | *** |
| 7 | log(BNCFreq) | 4.1763 | 0.0339 | 0.0012 | 28.6367 | *** |
| 8 | res(log(SbtlFreq)) | 4.1742 | 0.0334 | 0.0017 | 19.7839 | *** |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Participant | 37 | 0.2049 | 0.4527 |
| NxtPrDel\|Pp | | 0.0005 | 0.0222 |

$$
\begin{aligned}
Correct(0-6) \;\sim\; & ManyFew/BeginEnd\{\mathrm{M-F},\ \mathrm{F-F},\ \mathrm{F-M},\ \mathrm{M-M}\} \;+ \\
& SyllableBreak\{\mathrm{Middle, Elsewhere}\} \;+ \\
& Plural\{\mathrm{no},\ \mathrm{yes}\} \;+ \\
& HandednessQuotient \;+ \\
& \log(BNCFrequency) \;+ \\
& residuals\left(\log(SubtitleFreq) \sim \log(BNCFreq)\right) \;+ \\
& \left(\sqrt{NextPressDelay} \mid Participant\right), \\
& \mathrm{model} \;=\; \mathrm{Poisson}
\end{aligned}
\tag{5.5}
$$

Figure 5.7: Model Equation for comparing Many vs. Few sublexical neighbourhood sizes, for target beginnings and endings

As predicted: $(i)$ targets that had beginnings with many sublexical neighbourhood counts and endings with few sublexical neighbourhood counts were the most accurately perceived (*line 0 in Table 5.4, Predict* value $= 4.037$); and $(ii)$ targets that had beginnings with few sublexical neighbourhood counts and endings with many sublexical neighbourhood counts were the most poorly perceived (*line 2, Predict* value $= 3.855$). However, while this categorisation of beginnings and endings into Many and Few identified the remaining two categories as falling in-between the *best* and *worst* cases above, the categorisation did not identify the "Many-Many" group (line 3) as significantly different from the "Many-Few" group. Perhaps the *goodness* of the word beginning activating a coarse-grain response in the RH is driving the positive result of word identification.

I continued to explore the Beginning and Ending contributions to correctness of word perception, but with the continuous $BeginScore$ and $EndScore$ variables (defined in Equations 5.1 and 5.2, page 88). Moving forward from the previous model with two-level categorical levels for each of the beginning and ending sublexical strings, these continuous measures refer to a directionality in the relative contributions of the word beginnings and word endings. The LMER statistical model for these variables is shown in Table 5.5 with Equation 5.6.

In this model, as the count of sublexical neighbours for word beginnings increases, the number of correct letter perceptions *increases* (line 1 in Table 5.5, shown by the positive value for model coefficient). As this LMER model is not the best model given the variables I used to define the model (see the following LMER models), the predicted value for $BeginScore$ is not within the bounds of the permitted dependent variable –number of correct letters– with a range from 0 to 6. The directionality is nevertheless

Table 5.5: Model statistics for $BeginScore$ and $EndScore$ main effects (Equation 5.6)

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Syll.Brk=Mid; Singular | 3.9426 | 3.6744 | 0.0574 | 63.9964 | |
| 1 | BeginScore | 6.7674 | 0.5403 | 0.0521 | 10.3767 | *** |
| 2 | EndScore | 3.4518 | -0.1329 | 0.0340 | -3.9077 | *** |
| 3 | Syll.Brk!=Mid | 3.9066 | -0.0092 | 0.0049 | -1.8844 | (.) |
| 4 | Plural | 3.8376 | -0.0270 | 0.0065 | -4.1239 | *** |
| 5 | HQ | 5.9208 | 0.4066 | 0.1160 | 3.5046 | *** |
| 6 | log(BNCFreq) | 4.0771 | 0.0335 | 0.0012 | 28.2558 | *** |
| 7 | res(log(SbtlFreq)) | 4.0718 | 0.0322 | 0.0017 | 18.9831 | *** |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Participant | 37 | 0.2047 | 0.4525 |
| NxtPrDel\|Pp | | 0.0005 | 0.0222 |

$$
\begin{aligned}
Correct(0-6) \;\sim\; & BeginScore \;+ \\
& EndScore \;+ \\
& SyllableBreak\{\text{Middle}, \text{Elsewhere}\} \;+ \\
& Plural\{\text{no}, \text{yes}\} \;+ \\
& HandednessQuotient \;+ \\
& \log(BNCFrequency) \;+ \\
& residuals\left(\log(SubtitleFreq) \sim \log(BNCFreq)\right) \;+ \\
& \left(\sqrt{NextPressDelay} \mid Participant\right), \\
& \text{model} \;=\; \text{Poisson}
\end{aligned}
\tag{5.6}
$$

Figure 5.8: Model equation for $BeginScore$ and $EndScore$ main effects

in the direction I predicted for a LVF/RH contribution, namely, a greater beginning sublexical size increases the processor's ability to perceive the target word.

In an opposite manner, a greater count of sublexical neighbours for word endings *decreases* the number of correct letter perceptions (line 2, shown by the negative model coefficient). Said another way, a *smaller* count of sublexical neighbours for word endings *increases* the number of correct letter perceptions. This directionality for ending sublexical neighbourhood size is also as I predicted for a RVF/LH contribution, namely that more unique endings of words increases the processor's ability to perceive the target word.

As before, the other main effects that I found in the base model were significant independent contributors to correct word perception (lines 3 through 7).

#### 5.4.3.5 Both Contralateral vs. Ipsilateral and $BeginScore$ and $EndScore$ experiment manipulations

I added presentation condition together with beginning and ending sublexical neighbourhood measures to the base model to test my predictions (shown in Table 5.6). As before, the ipsilateral presentation condition (line 1) was significantly less correctly perceived than the contralateral presentation condition (included in the intercept, line 0); Z-score = -4.087, $p < 0.001$. The actual size of the difference has diminished, with 3.681 down to 3.668 for the predicted correctness values for the contralateral and ipsilateral presentation conditions respectively.

As in the previous model, a larger beginning sublexical neighbourhood size (line 2) increases the probability of correct word perception, as does a smaller ending sublexical neighbourhood size (line 3); both covariates were highly significant, with Z-score = 2.874, $p < 0.01$ for $BeginScore$ and Z-score =-5.077, $p < 0.001$ for $EndScore$. The

Table 5.6: LMER model statistics for both Contralateral vs. Ipsilateral and $BeginScore$ and $EndScore$ main effects together (Equation 5.7)

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Contralateral; Syll.Brk=Mid; Singular | 3.6815 | 3.6815 | 0.0574 | 64.1809 | |
| 1 | Ipsilateral | 3.6682 | -0.0133 | 0.0040 | -3.3385 | *** |
| 2 | BeginScore | 3.9063 | 0.2249 | 0.0724 | 3.1054 | ** |
| 3 | EndScore | 3.4926 | -0.1888 | 0.0421 | -4.4882 | *** |
| 4 | Syll.Brk!=Mid | 3.6720 | -0.0095 | 0.0049 | -1.9418 | (.) |
| 5 | Plural | 3.6544 | -0.0271 | 0.0065 | -4.1332 | *** |
| 6 | HQ | 4.0881 | 0.4066 | 0.1158 | 3.5098 | *** |
| 7 | log(BNCFreq) | 3.7150 | 0.0336 | 0.0012 | 28.2725 | *** |
| 8 | res(log(SbtlFreq)) | 3.7138 | 0.0323 | 0.0017 | 19.0196 | *** |
| 9 | Ipsilateral:BeginScore | 4.5309 | 0.6379 | 0.1020 | 6.2561 | *** |
| 10 | Ipsilateral:EndScore | 3.5934 | 0.1141 | 0.0505 | 2.2584 | * |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Participant | 37 | 0.2050 | 0.4527 |
| NxtPrDel\|Pp | | 0.0005 | 0.0222 |

$$
\begin{aligned}
Correct(0-6) \;\sim\; & Condition\{\text{Contralateral}, \text{Ipsilateral}\} * ( \\
& BeginScore \; + \\
& EndScore \; ) \; + \\
& SyllableBreak\{\text{Middle}, \text{Elsewhere}\} \; + \\
& Plural\{\text{no}, \text{yes}\} \; + \\
& HandednessQuotient \; + \\
& \log(BNCFrequency) \; + \\
& residuals(\log(SubtitleFreq) \sim \log(BNCFreq)) \; + \\
& \left(\sqrt{NextPressDelay} \mid Participant\right), \\
& \text{model} \; = \; \text{Poisson}
\end{aligned}
\tag{5.7}
$$

Figure 5.9: Model equation for both Contralateral vs. Ipsilateral and beginning and ending sublexical neighbourhood counts

predicted value of 3.906 for the unit increase in $BeginScore$ is now within the bounds of the dependent variable (0 through 6).

I found a significant contribution to the LMER model fit for the interactions between mode of presentation and both beginning and ending sublexical sizes, as I had predicted. One unit increase in $BeginScore$ makes the predicted value of correctness for the ipsilateral presentation jump from 3.668 (line 1 in Table 5.6) up to 4.531 (line 9). This is larger than the increase that $BeginScore$ has on contralateral presentation, from 3.681 (line 0) up to 3.906 (line 2).

Furthermore, a unit increase in $EndScore$ drops the predicted value the ipsilateral condition from 3.668 (line 1) down to 3.593 (line 10). Also, this is a smaller than the decrease that $EndScore$ has on contralateral presentation, from 3.681 (line 0) down to 3.493 (line 3). I included eye preference ($EQ$) into the model, but it did not explain any model variance, nor did it interact with either $BeginScore$ or $EndScore$ (data not shown).

To make these relationships more explicit, I show the model prediction values for the effects that $BeginScore$ and $EndScore$ have on contralateral and ipsilateral presentations in Table 5.10. Clearly, $BeginScore$ has most of an effect for ipsilateral presentations, and $EndScore$ has most of an effect for contralateral presentations. Interestingly, both of these situations only occur for significantly the Right Eye in my experiment. Correspondingly, the Left Eye is associated with the smallest changes due to beginning and ending sublexical effects.

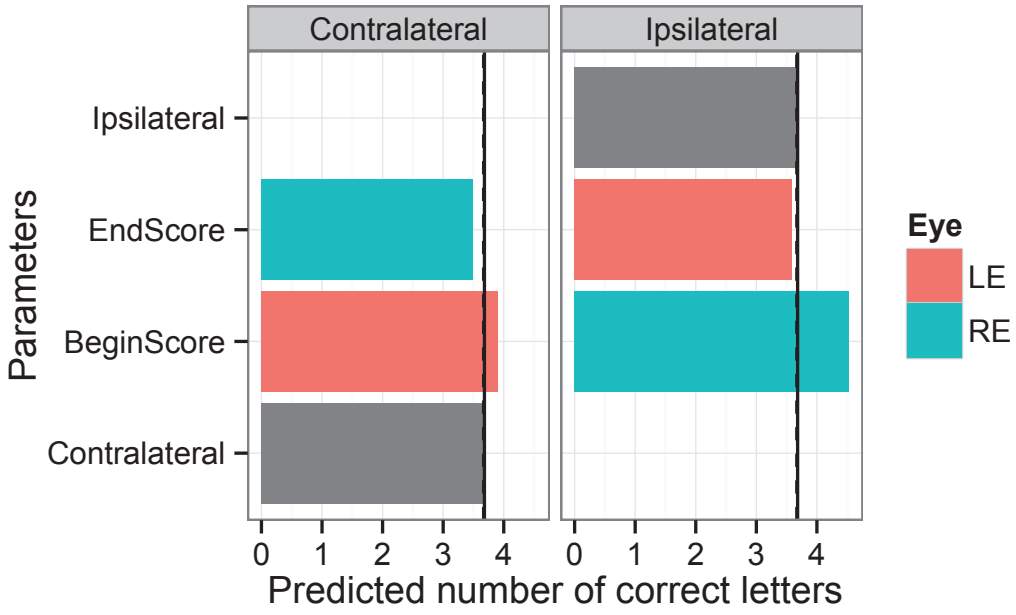


Figure 5.10: Effects that $BeginScore$ and $EndScore$ have on contralateral and ipsilateral presentations. Vertical solid and dashed lines correspond to the neutral values for the contralateral and ipsilateral presentations, respectively. Eye receiving beginning and ending stimuli is highlighted in colour.

#### 5.4.3.6 Interactions between Beginning and Ending effects with Sex and handedness

If these beginning and ending effects are due to separate hemispheric processing, then there should be an interaction with variables that typically associate with lateralisation. For this post-hoc analysis, I used $Sex$ and Handedness Quotient, $HQ$. Specifically, while Males typically express more language functionality in the LH, Females typically show more distributed activation in both hemispheres (see Kansaku, Yamaura, and Kitazawa (2000); Shaywitz, Shaywltz, Pugh, Constable, Skudlarski, Fulbright, Bronen, Fletcher, Shankweiler, Katz, and Gore (1995); however, see Ihnen, Church, Petersen, and Schlaggar (2009) for issues with BOLD group comparisons).

I used LMER modelling to explore the interactions of beginning and ending sublexical neighbourhood counts with both sex and handedness; these interactions are shown the LMER model shown in Table 5.7 (Equation 5.8). As is in the previous models, ipsilateral presentation fares less well than contralateral presentation, and $BeginScore$ and $EndScore$ have their respective fine-grain and coarse-grain effects on correctness of word perception. Statistically, Males and Females are not significantly different. Line 3 in Table 5.7 shows a non-significant difference between these two groups in contralateral

Table 5.7: LMER model statistics for the interaction of sex and handedness with beginning and ending sublexical neighbourhood counts (Equation 5.8)

Fixed Effects

| | Parameter | Predict | Mdl.Coeff. | Std.Err. | z value | |
|---|---|---|---|---|---|---|
| 0 | Contralateral; Male; Syll.Brk=Mid; Singular | 3.6980 | 3.6980 | 0.0842 | 43.9437 | |
| 1 | Ipsilateral | 3.6844 | -0.0136 | 0.0040 | -3.4123 | *** |
| 2 | Male:HQ | 4.2123 | 0.5143 | 0.2516 | 2.0443 | * |
| 3 | Contralateral; Female | 3.6676 | -0.0304 | 0.1147 | -0.2649 | (ns) |
| 4 | Male:BeginScore | 4.1451 | 0.4471 | 0.0761 | 5.8746 | *** |
| 5 | Male:EndScore | 3.4469 | -0.2510 | 0.0436 | -5.7556 | *** |
| 6 | Syll.Brk!=Mid | 3.6885 | -0.0095 | 0.0049 | -1.9440 | (.) |
| 7 | Plural | 3.6708 | -0.0271 | 0.0065 | -4.1456 | *** |
| 8 | log(BNCFreq) | 3.7315 | 0.0335 | 0.0012 | 28.2273 | *** |
| 9 | res(log(SbtlFreq)) | 3.7304 | 0.0324 | 0.0017 | 19.0767 | *** |
| 10 | Female:HQ | 4.0405 | -0.1414 | 0.2836 | -0.4986 | (ns) |
| 11 | Male:HQ:BeginScore | 3.3555 | -1.3039 | 0.2191 | -5.9521 | *** |
| 12 | Male:HQ:EndScore | 4.8176 | 0.8563 | 0.1091 | 7.8507 | *** |
| 13 | Female:BeginScore | 4.3348 | 0.2202 | 0.1027 | 2.1435 | * |
| 14 | Female:EndScore | 3.5991 | 0.1826 | 0.0510 | 3.5779 | *** |
| 15 | Female:HQ:BeginScore | 4.7885 | 1.3846 | 0.2662 | 5.2006 | *** |
| 16 | Female:HQ:EndScore | 4.1325 | -0.6959 | 0.1333 | -5.2216 | *** |

0: Intercept case. Significance levels: . $< 0.1$; * $< 0.05$; ** $< 0.01$; *** $< 0.001$

Random Effects

| Groups | N | Variance | Std.Dev. |
|---|---|---|---|
| Participant | 37 | 0.2097 | 0.4579 |
| NxtPrDel\|Pp | | 0.0005 | 0.0222 |

$$
\begin{aligned}
Correct(0-6) \;\sim\; & Condition\{\text{Contralateral}, \text{Ipsilateral}\} \; + \\
& HandednessQuotient \; * \\
& Sex\{\text{Male}, \text{Female}\} \; * \\
& [\; BeginScore \; + \\
& \quad EndScore \;] \; + \\
& SyllableBreak\{\text{Middle}, \text{Elsewhere}\} \; + \\
& Plural\{\text{no}, \text{yes}\} \; + \\
& \log(BNCFrequency) \; + \\
& residuals\left(\log(SubtitleFreq) \sim \log(BNCFreq)\right) \; + \\
& \left(\sqrt{NextPressDelay} \mid Participant\right), \\
& \text{model} \; = \; \text{Poisson}
\end{aligned}
\tag{5.8}
$$

Figure 5.11: Model equation for the interaction of sex and handedness with beginning and ending sublexical neighbourhood counts

presentations. However, interactions between Males and Females with other parameters are significant, and I show these separately in Figure 5.12.

In Figure 5.12 I have drawn four vertical lines to help with the comparisons: $(i)$ The solid line corresponds to the value for contralateral presentations for Males (line 0 in Table 5.7, the intercept); $(ii)$ the dashed line corresponds to the value for a unit increase in $HQ$ for Males (line 2 in Table 5.7, $p < 0.01$); $(iii)$ the dotted line corresponds to the value for a unit increase in $BeginScore$ for Males (line 4 in Table 5.7, $p < 0.001$); and $(iv)$ the dotted-dashed line corresponds to the value for a unit increase in $EndScore$ for Males (line 5 in Table 5.7, $p < 0.001$).

While unit increases in both $HQ$ and $BeginScore$ increase the number of predicted correct letters for Males, their interaction ("Male:HQ:BeginScore", also line 11 in Table 5.7) decreases. Inversely, the interaction "Male:HQ:EndScore", (also line 12 in Table 5.7) increases. My explanation for these three-way interactions is that strongly lateralised Males (characterised by HQ) do not take advantage of beginning (LVF/RH) sublexical features, and do take advantage of ending (RVF/LH) sublexical features (cf., Welcome et al., 2009).

Females perform similarly to Males in both contralateral presentations and $HQ$ (lines 3 and 10 in Table 5.7 respectively). Likewise, unit increases in $BeginScore$ and $EndScore$ have similar positive and negative effects for correctness of word perception as for Males (lines 13 and 14 in Table 5.7 respectively). However, Females with unit increases in $HQ$ perform significantly better than Males with unit increases in $BeginScore$ ("Female:HQ:BeginScore", also line15 in Table 5.7). Like Males, the interaction with

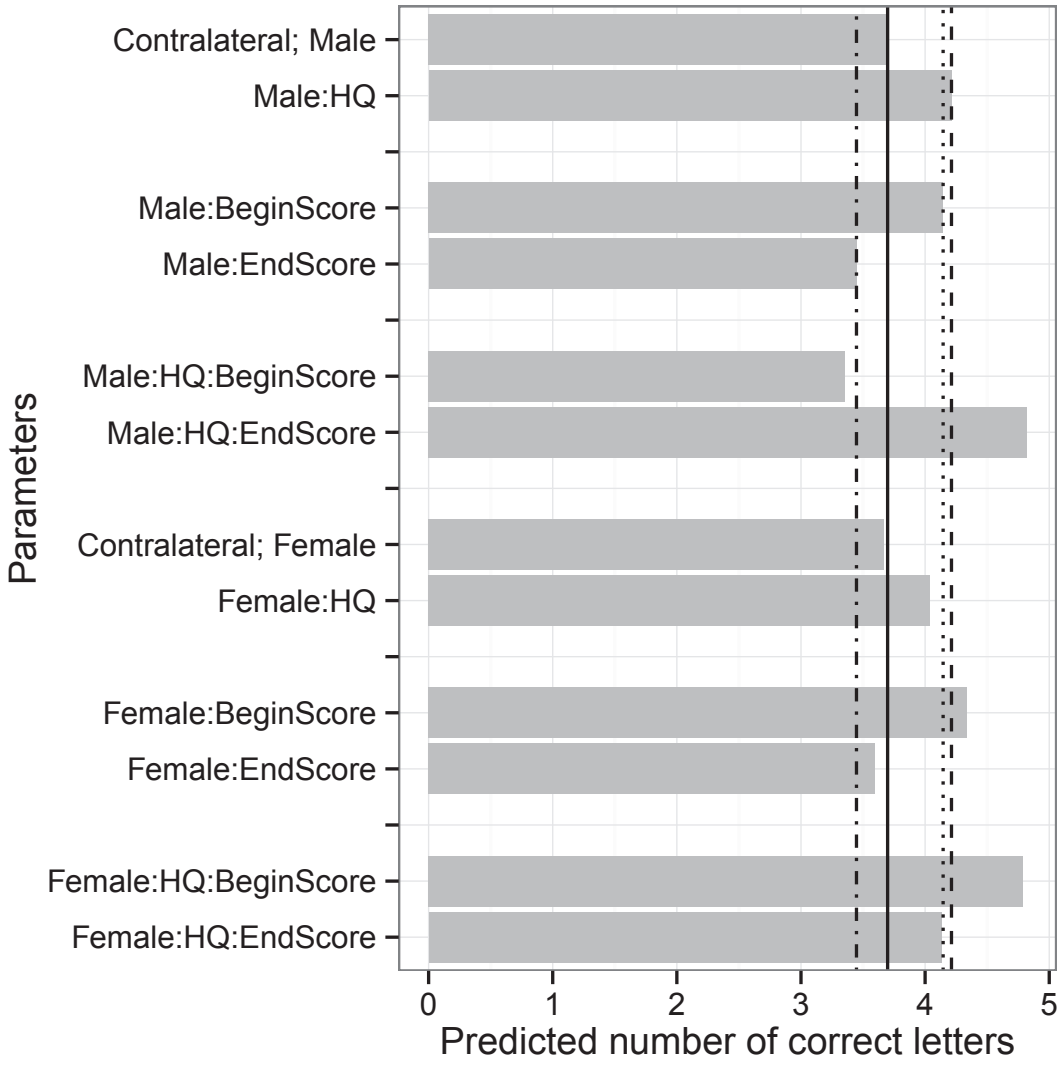


Figure 5.12: Interactions between Handedness Quotient ($HQ$) and $Sex$ with $BeginScore$ and $EndScore$. Vertical lines are drawn to facilitate comparison of the top four horizontal parameter bars to the other parameter bars (see text for details).

$HQ$ and $EndScore$ has a positive effect on correctness of word perception, albeit not as much as for Males. My explanation for these Female three-way interactions is that Females take advantage of beginning sublexical features (LVF/RH), showing a lateralisation different from Males. That is, while Males rely heavily on RVF/LH features, Females take advantage of both RVF/LH and LVF/RH features.

## 5.5 Discussion

According to SFT, a fixated word would be divided vertically according to the foveal centre for each eye, projecting the left and right letter sequences to each hemisphere.

This initial division of information would afford a processing advantage if the two hemispheres were empowered to contribute to the recognition of the word independently, instead of just the LH carrying out all the work resulting from a bilateral projection from the fovea. Furthermore, the division of the word into beginning and ending sublexical components could allow each hemisphere to specialise on the sublexical properties resulting from separate hemispheric functional predisposition.

Given that we are continuously fixating on text as we carry out the process of reading, as well as the fact that we typically make several fixations on longer words, the contributions of the two hemispheres will arise from the processing of sublexical components that sometimes are to the right of fixation and sometimes to the left of fixation. While the separate contribution of the two hemispheres to the processing of these sublexical forms is already applying *twice the processing power* of the brain (as opposed to just the LH carrying out all the work), it would be even more advantageous for the two hemispheres to use their different functional predispositions to develop different strategies in the processing of these sublexical forms.

Thus, Experiment **VI** was designed to see if there were separate patterns of behaviour for the beginning and ending parts of words. I used the haploscope with conjointly presented half words (as in Exp. **I**) as a method of presenting the beginning and endings uniquely and separately to each hemisphere. Unlike Exp. **I**, I used six letter words that provided a wider range of possibilities for beginning and endings sequences.

I decided to construct a metric for quantifying the statistical properties of these sublexical forms that was based exclusively on the statistical properties of beginning and ending strings of letters, instead of using whole-word metrics, like for example the set of other words that have just one letter different from the target word used by others (e.g., Davis and Perea, 2005; Lavidor et al., 2004; Perea et al., 2008). The purpose of this metric was to select a range of target words that spanned the set of possible beginning and ending sequences based on their statistical likelihood of occurrence in the written language (English words taken from the British National Corpus). As such, I used the normalised type-count size of the beginning and ending one, two, and three-letter sequences from five through seven letter words. This metric spanning a continuous range would thus allow me to use beginning and ending values as separate covariates in my statistical analysis.

Again, the results from Exp. **VI** showed that the contralaterally presented half words are more significantly correctly reported than the same half words presented ipsilaterally. I also found that the beginning and ending type-count neighbourhoods did explain a significant portion of the variance in people's ability to correctly name the letters in the target word. Furthermore, beginning and ending statistics contributed in opposite manners to the overall ability to correctness of response: $(i)$ Beginning sublexical forms

(projected to the RH) with larger type-count neighbourhood sizes were more correctly identified than sublexical forms with fewer type-count neighbourhood sizes; and $(ii)$, Ending sublexical forms (projected to the LH) with smaller type-count neighbourhood sizes were more correctly identified than ending sublexical forms with larger type-count neighbourhood sizes.

These results apply for single word recognition, but, *How does the brain incorporate visual stimuli across time?* I will leave this question for future research.

## 5.6 Chapter conclusions

In this chapter I explored the sublexical neighbourhood effects of the left and right halves of a single word. Firstly, and as an extension of the finding in Chapter 3, contralateral presentation of the stimuli produced more correctly identified letters (in correct order) than ipsilateral presentation. This result applied for both Males and Females. Secondly, word endings that occurred in many words produced *less* correct letter identifications than word endings that occurred in only a few words. Thirdly, word beginnings that occurred many times produced *more* correct letter identifications than word beginnings that occurred in only a few words. Moreover, I found that type-count word beginnings and endings interact with Sex and HQ, such that Males show more LH word ending effects and Females show both LH and RH word ending and word beginning effects, respectively. HQ reinforced these Sex differences. Finally, beginning and ending effect sizes were more strongly mediated by the right eye than the left eye.

In the following chapter I will develop a proposal for a bihemispheric account of word recognition that is based on these beginning and ending many versus few sublexical effects.

# Chapter 6

# The resonance model of neighbourhood effects

## 6.1 Chapter overview

This chapter lays out the design for a neural network to represent the two hemispheres carrying out the task of perceiving a word; its design was inspired by the results for my experiments contained in this thesis. The hypothesis is that the trained network would continue to find emergent hemispheric effects for perceiving words. While the network I propose is not contingent on word lengths, it does suppose statistical exposure to written text as would be perceived by a human through years of experience.

## 6.2 A neural network for word recognition

Current computational models of word recognition (for both isolated words and text) have been inconclusive in producing results that compare competing models against critical new data and against benchmark data. Neither is there any substantial convergence of the models, and, there appears to be no general desire to augment the models with more real-world detail (such as binocular input).

Recently, Grainger and Ziegler (2011) have proposed that the brain could use a dual-route approach for encoding letter strings into whole-word orthography and semantics. In their description of their theoretical proposal, Grainger and Ziegler describe how visual features would initially encode letters (interestingly, no mention is made regarding two eyes or brain lateralisation of the visual input) that would be passed along two routes to separate procedures for $(i)$ coarse-grained orthographic processing (e.g., "open bigrams") and $(ii)$ fine-grained orthographic processing (e.g., substrings for the ends and for the middle regions of the words. They then propose that these very explicit sublexical components could be used in procedures analogous to String Kernels in computational science (Herbrich, 2002; Hofmann, Schölkopf, and Smola, 2008; Hannagan and Grainger, 2012; Jäkel, Schölkopf, and Wichmann, 2009) to arrive at the target word (Hannagan and Grainger, 2012).

Shillcock and Monaghan (2001) proposed a computational model for visual word recognition with separate left and right inputs that connected to separate left and right

hidden layers, that finally connected to a unified output layer. The model was designed to parallel the SFT concept of anatomical structure, and intended to show how SFT could account for a preferential role for the first and last letters in a word, which has been amply reported in psycholinguistic experiments. The input for their computational model consisted of four letter words (where each letter was encoded with eight units) that were presented across the left and right input vectors.

### 6.2.1 Understanding word recognition by modelling

Conventional research in the theoretical and computational modelling of reading at the level of the single word level and at the text level typically idealises the processing in a number of ways, simplifying the component parts of any model, and simplifying the model itself, often excluding key components (such as attention, or binocular input) that may feature in other models, and aiming for a particular type of generality. (See Churchland, Ramachandran, and Sejnowski, 1994, for a seminal critique of the idealisation of "pure vision" encapsulated from the motor system; see Weisberg, 2007, for a contemporary review of approaches adopted by philosophers of science towards idealisation and abstraction.)

One way that the cognitive science community has approached the problem of understanding reading has been by tackling the sub-problem of identifying an isolated word. Experiments on the recognition of isolated words, distinguishing them from plausible non-word strings, constitutes one of the largest research sub-domains in experimental psychology. However, it is in the fluent, expert reading of connected text by adults that we see the fully developed, normal form of reading.

The brain and the eyes did not evolve for reading but for helping us interact with –and react to– objects in depth. The physical aspects of reading (orthography, texts, alphabets) are cultural products that have developed to fit in to the niche represented by our evolved cognition. In this sense, reading is particularly informative of the functional nature of the brain and cognition, and is simultaneously perhaps our most "human" activity. It is also a supremely sophisticated physical mechanism and information system, both operating in tight synchrony.

Psychologists have been relatively successful in characterising and modelling some aspects of reading behaviours, particularly those involving isolated words, partly because the dimensions of the problem are known (we can list all the words a reader needs to know) and partly because words and text contain a number of levels of description, all with rules of combination – letters, morphemes, content words, functors, syntactic constituents, sentences. Numerous psycholinguistic experiments have characterised sub-word structure, either in formal terms (e.g. morphemes, graphemes) or in pragmatic terms (e.g. letter pairs with one or more intervening letters), and the functional nature

of the similarities and differences that exist between the words in the mental lexicon (e.g., Andrews, 1996, 1997; Stevens and Grainger, 2003).

This view of the structure of language has led cognitive scientists to implement computational models of the ways in which a fixated word might partially activate smaller or larger numbers of similar words in the mental lexicon (cf. Harm and Seidenberg, 2004). Thus, the printed word bolt might partly activate stored representations of colt, dolt, belt, blot, boat, boll and bole, among others. Different bases for such similarities between words have led to theories of the storage and activation of lexical representations, and to successful computational models that implement such theories.

Computational models of lexical processing have been one of the flagships of cognitive science research, employing a range of assumptions about the nature of the representations and their criteria for comparison, together with assumptions about the algorithms used to maintain and compare such representations. Computational models extend the intuitions of researchers and make testable predictions for further human experimentation. They also allow qualitative aspects of brain function to be incorporated into computational models; such idealisations allow us to refine further our conceptual understanding of the processing involved. Thus, the exploration of parallelism in connectionist models has been one of the major research issues over the last two decades.

### 6.2.2 The hemispheric division of the brain

One of the aspects of brain function that has been less well-represented in the computational modelling of lexical processing has been hemispheric differences, although see Monaghan et al. (2004) and Weems and Reggia (2004) for successful examples of such research.

Several models of word recognition respect the fundamental architectural fact about the brain, namely, that it is divided into two cerebral hemispheres. Researchers have long recognised the fact that lexical processing is typically facilitated when a stimulus word is presented in the right visual field, meaning that it is initially projected exclusively to the left hemisphere, which is known to be typically specialised for language processing. However, the mechanism by which information is transferred between the hemispheres is usually simplified to one of physical, all-or-none transfer, with the hemispheric division of the brain being seen as more of an inconvenience to processing, than as a computational opportunity to encapsulate, temporarily and partially, different kinds of processing and conduct them in parallel before allowing their informational co-ordination to emerge.

A productive research strategy has been to make strong assumptions about the encapsulation of the two hemispheres in order to explore other mechanisms of hemispheric co-ordination. The successful post-operative lives of callosotomised ("split-brain") individuals is a critical observation in this respect, particularly the fact that such patients

can outperform normal participants on certain divided-attention tasks (cf. Luck, Hillyard, Mangun, and Gazzaniga, 1994).

An important dimension of hemispheric processing is the proposed distinction between right-hemisphere coarse-grain processing and left-hemisphere fine-grain processing. Although this typical distinction has interesting exceptions (e.g., Mevorach, Humphreys, and Shalev, 2005), it has yielded a number of important insights about brain function (e.g., Beeman, Friedman, Grafman, Perez, Diamond, and Lindsay, 1994). In this view, coarse-coding means that any one computational unit is involved in a wider range of representations than an otherwise comparable fine-coding unit. The metaphor of a larger receptive field in coarse-coding expresses the same distinction.

Some computational models of lexical processing (e.g., Shillcock et al., 2000, 2010; Whitney, 2001) implement the fact that the hemispheric division of the human brain extends out as far as the fovea, the highest fidelity region of the retina, meaning that a single fixated word can be divided in its projection to the two hemispheres of the brain. Shillcock et al. (2010) model this range of variation and show similar implications for visual word recognition, stemming from the sharp offset in the hemifield projection across the fovea, a fact that has different implications from any level of bi-hemispheric projection that may be present.

### 6.2.3 Eye-movements in reading

The movements of the eyes across a page of text during reading represent a striking challenge to researchers wishing to understand the physical, neuroanatomical, neurophysiological and cognitive aspects of such movements. The eyes move in a yoked manner across the page, with fixation durations of the order of 200 ms alternating with saccades, frequently skipping one or more words, frequently refixating forwards or backwards within the same word, and occasionally regressing to a previous point in the current line or a previous line (Rayner, 1998). On any one fixation there may be a parafoveal preview of the next word(s), which may contribute to their recognition when they are subsequently fixated. The eyes often fixate more or less conjointly, no more than a letter apart, but there can also be surprising disparities of two or more letters, sustained during and between fixations (Liversedge et al., 2006b; Nuthmann and Kliegl, 2009). This binocular disparity has been claimed to be adaptive (Shillcock et al., 2010), expanding the foveal window onto the text and dictating which of two depth-processing domains will be responsible for the formation of the stereo image in the cortex.

The pattern of movements made by the eyes has been extensively recorded in many languages. There are commonalities between the languages but also surprising qualitative and quantitative differences (Pynte, Kennedy, and Ducrot, 2004; cf. Share, 2008) in the parameters of the movements. Eye-movements in reading are best understood as

an adaptive compromise between the cognitive demands of reading, the physical constraints of the task, and the neuroanatomical constraints of the visual system. Even what has often been construed as noise or error in the visual system may also be used adaptively by the brain in pursuit of the goals of reading.

One lacuna in the modelling of eye-movements in reading has involved an actual model of visual word recognition. In many models of eye-movements in reading, the process of word identification is very often a cipher which is not implemented in any detail, and certainly never with any neuroanatomical constraints, although neuroanatomically motivated models of word recognition exist in the literature on isolated word recognition (cf. Perry et al., 2007).

Finally, some of the predictions of models of eye-movements, hemispheric differences and word recognition converge on an observation by McDonald and Shillcock (2005) that there is a clear tendency for the informational demands on the two hemispheres to alternate backwards and forwards between successive fixations in the reading of text. In nearly 70% of fixations a measure of lexical uncertainty in each hemisphere was rising in one hemisphere as it was simultaneously falling in the other hemisphere, under the assumptions incorporated in the SERIF model of eye-movements in reading based on the vertical splitting of the human fovea (McDonald et al., 2005).

## 6.3 A Model of visual word recognition across the two hemispheres

After confirming a behavioural difference between contralaterally and ipsilaterally presented words (Chapter 3), and using this together with the controlled-for beginning and ending type-count neighbourhood sizes to find specific coarse-grain (right hemisphere) and fine-grain (left hemisphere) hemispheric strategies (Chapter 5), I propose a model of visual word recognition that is inspired by these results.

The assumption of RH coarse-coding means that presentation of a part-word directly to the LVF results in an aggregate activation in the RH of all the processing that potentially matches that part-word. This processing can be vision-related, auditory-related, and meaning-related in all its aspects. This is the kind of aggregate processing that underlies summation priming (Beeman et al., 1994). It is understandably slower to rise than activation in the LH (Simpson, Peterson, Casteel, and Burgess, 1989), due to the different aspects of such diffuse activation. The advantage of this aggregate activation is that it very probably contains the most relevant processing (i.e., the processing directly relevant to the word of which the part-word that is visible in the LVF). The disadvantage is that it is diffuse and not specific enough; the irrelevant aspects of the processing have to be filtered out.

Meanwhile, the assumption of LH fine-coding means that the complementary part-word in the RVF causes a very specific constellation of processing to appear rapidly

in the LH. The LH is predisposed to a categorical response, which may be seen as simply another aspect of fine-coding. The advantage of this specific processing is that a hypothesis about the most relevant constellation of visual, auditory and semantic processing is very quickly available, and typically it will be associated with the most frequent (and/or the least contextually specified) word that is compatible with the part-word (Simpson et al., 1989; Adelman, Brown, and Quesada, 2006; McDonald et al., 2005). The disadvantage is that there is a good chance that this maximally activated processing will be inappropriate; `single` will be "recognized" when the actual whole word is `mingle`.

Thus, we see that the two hemispheres present with complementary strengths and weaknesses. I wish to explore how the coordination of the two hemispheres can arrive at the best of both worlds and avoid the worst of both worlds.

The best of both worlds means that the LH helps to specify the most appropriate processing in the RH, and the RH helps to nudge the LH out of an inappropriate "local minimum" and to use the density of appropriate processing that is present in the RH for the "wrong" reasons (as when a lexical neighbour of the real whole-word results in at least partially appropriate processing). This more dense processing can reinforce the eventual desired constellation of processing.

The worst of both worlds would be if the maximally activated specific processing in the LH misleads and delays the RH by providing an incorrect hypothesis, and if the RH delayed the LH by diffusing the LH constellation of processing with non-specific noise.

An important strategy in this thesis has been to take the strongest hypothesis of complete independence of the two cerebral hemispheres and to see how far this assumption can be taken before it has to be relaxed. There is certainly hemispheric coordination across the ~250 million fibres that pass through the corpus callosum and connect the two hemispheres. In visual processing we see that neurons activated by elements in the visual scene become increasingly responsive to both hemifields as distance from V1 increases (Berlucchi and Antonini, 1990); visual processing seems to become more concerned with the whole visual field as opposed to specific hemifields, although the maximal response of such neurons is still typically to the contralateral hemifield. Conventionally, many psychologists and cognitive scientists jump straight to the abstract representation of the problem of visual recognition in reading and assume that any division of the visual field at the fovea has only a limited influence and is quickly transcended as language-related processing is concentrated in the LH (Hunter et al., 2007; Forget et al., 2010).

However, the analysis and modelling I propose here makes a surprising prediction, and goes against the conventional assumption that the hemispheric division is quickly transcended. We have seen above that the worst of both worlds involves the mutual contamination of each hemisphere's set of processing hypotheses. If the processing

associated with midway were to be projected throughout the LH in a processing strategy that assumed that foveal splitting and hemispheric autonomy were quickly transcended, and if the LH were to try to process the single, aggregate signal, then we would seem to have the worst of all worlds. Instead, the surprising prediction is that it is advantageous for the two hemispheres to exploit their respective expertises by maintaining hemispheric autonomy. This point will become clear as we consider the processing of the word mingle (Figure 6.1).

The model's operation (schematised in Figure 6.1) is described in terms of the following stages. I use the foveated word, mingle, as an example to highlight the working of this network.

1. The model receives stimulus input from the two eyes, represented by a signal derived from the visual input (this could be an instantiation of a Gabor filter, for instance). Crucially, this model is not couched in terms of any specific encoding of letters or letter-based entities.
2. This visual input is divided at the human foveas, so that the stimulus for the left part of the word is projected to the right half of the model (the model's "right hemisphere") and the stimulus for the right part of the word is projected to the left half of the model (its "left hemisphere") from both eyes separately. Importantly, there is no other need for position-encoding parts of the signal; just the provenance of the signal will suffice (cf. Bellamy and Shillcock, 2007, in which the hemifield provenance of a brief visual word stimulus is shown to be surprisingly persistent in processing).
    - In Figure 6.1, the word mingle is divided into left-eye and right-eye hemifoveal components at the top of the figure. Note that the two eyes are making a cross-eyed fixation on the word, and visual information for the letter 'n' is duplicated across the two hemispheric inputs. A similar outcome could emerge from a precisely conjoint fixation by the two eyes but in the middle of a letter, such that partial information about that middle letter went directly to both hemispheres.
3. The left and right visual field signals are passed to the right and left hemispheres respectively.
4. The state of the processing is shown in the top two rectangles in Figure 6.1. Note that no spatial isomorphism is necessarily intended between the horizontal extent of the part-words and the signal itself. Rather, the signal can be thought of as a non-spatial snapshot of a signal at a particular point in time. The red signal corresponds to the veridical information received by the LH and the green signal the veridical information received by the RH.

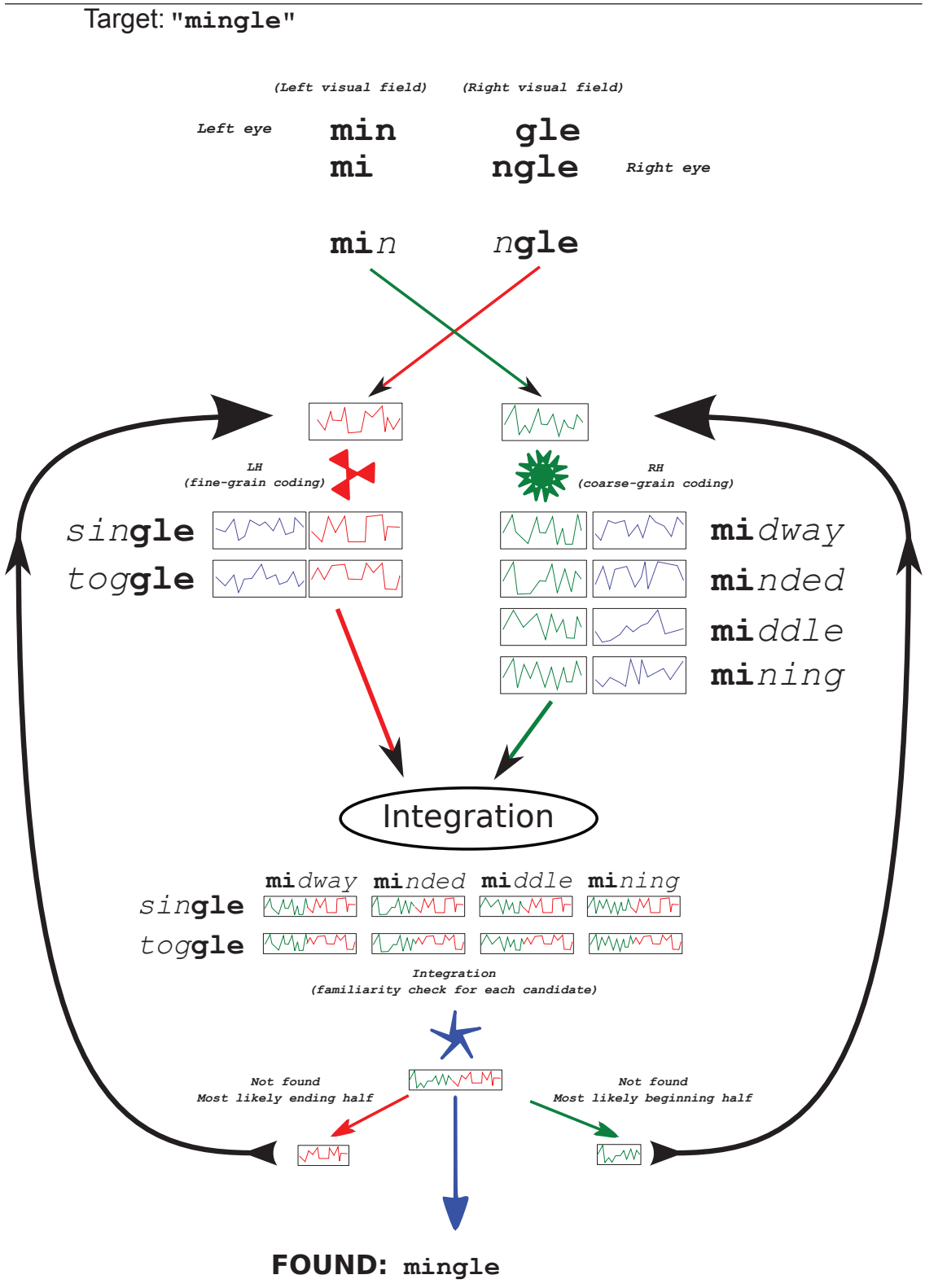


Figure 6.1: A two-tier artificial neural network for word perception. The target word "mingle" is viewed with a crossed-fixation disparity such that the RE is focusing to the left of the word and the LE is focusing on the middle of the word. Only the separate hemispheric processing of visual perception is taken into account.

Resonance initially occurs separately in the two halves of the model. The LH of the model generates activation states that are associated with past experience of lexical entries whose right-side signal component resembles the right-side input signal, and the RH of the model generates activation states that are associated with those lexical entries whose left-side signal component most resembles the left-side input signal.

Different parameters apply to this matching process in the two hemispheres. The model's LH has a fine-coding processing propensity similar to that demonstrated in Chapter 5, and results in a single composite activation state associated with a small number of candidates that best match that hemisphere's (rightmost) part-word input. Conversely, the model's RH operates with coarse coding, so that it generates a composite activation state that is associated with a relatively large number of lexical entries that loosely match the corresponding left part of the input signal (also shown in Chapter 5).

- Figure 6.1 shows that the model's LH effectively entertains a cohort of two candidate word signals: `single` and `toggle`. Likewise, the model's RH effectively entertains a cohort of four word signals: `midway`, `minded`, `middle` and `mining`.

5. Each hemisphere thus has a state of activation that reflects its initial input and its processing preferences. Note that these processing preferences can be not just generic fine- and coarse-coding but can also be particular types of cognitive processing (e.g. differential syntactic, phonological and semantic processing) that does not necessarily reflect the fine/coarse distinction.
6. The single composite activations reflecting the candidate word cohorts from both hemispheres are passed on to an integration phase, which essentially uses summation to add the signals together to generate a new single composite activation state associated with a new cohort of candidate activation profiles. This summation function is necessarily skewed towards emphasising the corresponding left-hemisphere endings and right-hemisphere beginnings in the process of producing the new list of candidates.

    - In Figure 6.1, the part of the model labelled "Integration" refers to this single activation state. The eight rectangles refer to the fact that the integration function effectively creates a composite activation state corresponding to non-existent candidate words. As such, these combined signals might not correspond to any activation profile entrained by previously encountered words. Importantly, no encoding or manipulating of letter information or hypothetical letter-based entities is being performed.

- In the example, the 2x4 list of integrated activation signals could correspond to {`midgle`, `mingle`, `midgle`, `mingle`, `midgle`, `mingle`, `midgle`, `mingle`}.

7. The integration stage is the point at which the two different hemisphere-based activation states come together. This does not need to happen at a specific anatomical location. Functionally speaking it is the coordination of the two hemisphere-specific states of activation. We will think of it as a single aggregate state of activation, again not necessarily respecting the spatial aspects of the word.
8. The single composite activation state corresponding to these integrated word signal candidates is then compared with the "lexicon" of previously entrained activation profiles. A criterial level of similarity to a stored representation constitutes the "familiarity check". Note that in a different computational implementation, such a comparison might correspond to predictive coding (e.g. Clark, 2013), for instance, based on the various aspects of the context in the reading of text.
    - In the example, the activation profile for `mingle` would resonate most strongly with the "lexicon" of activation profiles and be selected.
9. If no criterial level of familiarity is achieved, then the most highly activated candidate word signal has its left and right parts re-entered into the earlier two right and left hemispheric processors, respectively, effectively entering the new candidate to the input stage.
10. The process iterates until the criterial level of familiarity is achieved, or the new word signal (composed of the left and right parts) is added as a new entry into the "lexicon". Thus, words are encoded by bilateral patterns of activation entrained by repeated exposure to these words. There is no need for the two hemispheres to be one-to-one time-aligned in their generation of candidate word signals. This is important given the different activation profiles demonstrated by Simpson et al. (1989).

Quantitative output of the model would consist of: $(i)$ number of cycles of the model needed to reach the criterial level of similarity; $(ii)$ numbers of candidates proposed in each of the hemispheric subdomains of the model; and $(iii)$ nature of the errors made by the model. The behaviour of the model would be compared with a baseline condition in which there is no vertical split –corresponding to the split fovea– dividing the two halves of the foveated word.

## 6.4 Existing data and empirical predictions

The Resonance Model described above in schematic implementational terms matches a number of existing lexical processing effects described in the literature, promising to model them more completely and more parsimoniously. These include:

1. The relative importance of beginnings and endings of words (cf. Chambers, Stokes, Janko, and Mattingley, 2006; Andrews, 1996, 1997). Because each hemisphere has most experience of the respective extreme ends of any word over the entire history of its fixations, then the model will behave as if the very end letters were somehow being given special priority. Note, however, that the explanation given here does not even assume particular letter representations, and hence is the most parsimonious demonstration of this end-letters effect.
2. Optimal viewing position (OVP) (Stevens and Grainger, 2003; O'Regan and Jacobs, 1992). The optimal viewing position for isolated words will emerge from the model because the model will process the word fastest if the information present on either side of fixation is equal (cf. Shillcock et al., 2000).
3. The Preferred Viewing Location (PVL) (Starr and Rayner, 2001) is the fixation location in a word in text at which readers prefer to fixate. It is typically left of the OVP for the same word presented in isolation. The model predicts this effect because the model is based on the complementary hemispheric distribution of information. The additional assumption is made that on the previous fixation(s) there will have been a parafoveal preview of the beginning of the critical word, projecting reliable information about the first one or two letters of the critical word. Thus the best place for a fixation on the critical word will be just beyond these previewed letters, so that the complementary part of the word is also projected to the LH.

   Most reading takes place with text, in contrast to psychologists' research orientation towards isolated word recognition. In the reading of English, the LH will typically receive whatever parafoveal preview is available of the next word or two to the right of the fixated word, and the RH will receive a parafoveal "post-view" of the word(s) to the left of the fixated word. The latter typically has fewer implications for processing, given that English has a left-to-right orthography. Such parafoveal views are veridical views that project directly to the relevant hemisphere, and it must be assumed (more critically for the LH) that trans-saccadic integration is possible. The addition of trans-saccadic integration to the model will produce a more complete model more able to capture the reading of text. Trans-saccadic effects will be particularly important for the modelling of agglutinating

languages such as Finnish in which the longer words will make very interesting demands on a model such as the current one.

4. Morphological and syllabic effects. Various researchers have shown apparent effects of the appearance of affixes (Taft, 1979; Taft and Krebs-Lazendic, 2013) and syllable boundaries in the recognition of isolated visual words. The graphotactic statistics intrinsic to such structures (e.g., frequent morphemes and pseudomorphemes such as re-, or de-, and the wider range of phonological transitions across syllable boundaries) ensure that apparent effects of morphology and syllabicity will emerge from processing even when that processing does not admit to specific letter-levels or morpheme levels.
5. Phrasal processing and word skipping. There is no reason why the Resonance Model cannot fixate somewhere in the middle of chunks of text such as wreak havoc or in the and elicit the "lexicalization" of such phrases. The model will treat the pair of words as parts of a larger constituent and allow them to be entered into the lexicon.
6. Multiple fixations of the same word. In the reading of text, the same word may be fixated more than once. O'Regan's strategy and tactics analysis (O'Regan and Lévy-Schoen, 1987) describes how the processor may make a strategic decision $(i)$ to fixate in the middle of a word, thus ensuring efficient processing of a short word with a single fixation, or $(ii)$ to fixate at the very beginning and at the end of a longer word, thereby ensuring that each hemisphere receives complementary information about the complete word. This procedure is the best way to ensure that the Resonance Model receives complementary and sufficient information in each half of the model.
7. Neighbourhood effects. Effects involving lexical neighbourhoods (e.g., Andrews, 1997) will emerge from the particularly those in which contrasting patterns of facilitation and inhibition are observed simultaneously in different parts of the same word.

## 6.5 Chapter conclusions

I have used the results from Chapters 3 and 5 to design a model of visual word recognition that embodies coarse-grain and fine-grain hemispheric processing. Its inputs are activation signals that correspond to the left and right sides of the fovea, for each eye. These signals feed the two separate halves of the model, as do the ocular pathways from the two sides of the retina to the two hemispheres.

Each half (corresponding to "hemispheres" of the model) then uses the combination of the two eye's signals to generate a cohort of complete word signal candidates: $(i)$ the left hemisphere of the model activates those word signals whose right sides most

closely correspond with its combined input signal from the eyes (a fine-grain processing strategy); and $(ii)$ the right hemisphere of the model activates those word signals whose left sides loosely correspond with it combined input signal from both eyes (a coarse-grain processing strategy).

The two sets of cohort signals are made available to a third stage of the model that integrates the right-hand parts of the "left hemisphere" candidates together with the left-hand parts of the "right hemisphere" candidates to produce a new set of candidate signals. A "familiarity check" is then carried out over this third set of candidate cohorts. If one of the integrated candidates succeeds in passing the familiarity check, the model produces this signal (corresponding to a word). Otherwise, the left and right side components of the most highly activated (resonant) signal are passed back to the corresponding right and left sides of the model for generating a new set of hemispheric cohorts. These are integrated together with whatever signals are coming from the eyes.

The overall model is intended to simulate the sophisticated co-ordination over time of the two hemispheres, as observed in my experiments and the cognitive neuropsychological literature. I have purposefully not used idealised representations like "open bigrams", but rather patterns of activations –signals– to represent words in the lexicon. Crucially, these signals have two sides to them that correspond with the perceptual inputs from the two eyes, which are produced from the vertical division of the fovea.

# Chapter 7

# Conclusions

The research in this thesis is aimed at better understanding how we perceive the written word with two eyes. My working hypothesis was that anatomy and hemispheric predispositions empower the brain to perceive text centrally shown to the two eyes. I found that word recognition is optimised when using contralateral pathways, and involves unique contributions from both hemispheres in a manner that reflects separate and complementary coarse-grain and fine-grain hemispheric strategies. I found that there is a unique and productive relationship between two eyes, the two cerebral hemispheres and a vertically divided central visual field.

For several years there has been a strong debate concerning the status of the Split Fovea Theory. Those arguing against, most notably Jordan and Paterson (2008), argue that the experiments to date have not proven the existence of a vertically split fovea, and are flawed in their design. Furthermore, they argue that anatomical evidence brought to bear on the matter is not appropriate as the relevant experiments were not designed to address a vertically split fovea. Furthermore, in their line of experiments –including the repetition of experiments published by supporters of the Split Fovea Theory– they found no direct evidence for a vertically split fovea.

Proponents of the Split Fovea Theory, exemplified by Ellis and Brysbaert (2010b), insist that their hypothesis is not only theoretically driven but also supported by their multiple experiments. Additionally, new lines of research using fMRI (Miki et al., 2001; Toosy et al., 2001) and scanning laser ophthalmoscopes (Reinhard and Trauzettel-Klosinski, 2003) showed promising evidence for the splitting of anatomical pathways from the eyes to the cerebral hemispheres, arguing that these anatomical features in humans could lead to functional traits in visual perception.

The question addressed in this thesis, *How do we perceive the written word?* was inspired by the debate regarding the status of a vertically split fovea. Furthermore, the above anatomical research showing evidence for hemispheric effects fuelled the design of a new experiment paradigm to test visual word recognition. If there are visual pathway differences (specifically from the two foveas to the two hemispheres), then

half words shown very briefly across the two eyes should result in behavioural differences. I constructed a haploscope, together with very carefully designed stimuli shown exclusively within the foveal region, to explore the recognition of words by able English readers under challenging conditions. I made extensive use of linear mixed effects statistical modelling to arrive at comprehensive models that used both correct and partially correct responses.

The results from my experiments showed that, as predicted, there is a contralateral pathway advantage in visual word perception. Also, while the conjoint viewing of words is best perceived, uncrossed disparities lead to better word recognition in the challenging task used; however, there was a greater role for visual saliency. Importantly, I found that visual word recognition is mediated by complementary processing in the two hemispheres. The left hemisphere was implicated with word endings that were more unique within the lexicon (a fine-grain strategy); the right hemisphere was implicated with word beginnings that were shared with many other words in the lexicon (a coarse-grain strategy). Furthermore, modelling the results with linear mixed effects statistics showed a role for other variables, for example, sex, handedness, syllabicity, plurals, and a right eye correlation with greater accuracy in word recognition.

I conclude with the design of a resonance model of visual word recognition that incorporates the anatomical features addressed in the thesis and the results from my experiments. It avoids using abstract entities like letters or "open bigrams" and instead uses activation signals from the two eyes. This bicameral model shows how and why a vertical division of the central visual field by the two eyes could provide the all-important function of word recognition.

The contribution of this thesis has been to provide new evidence for the vertical splitting of the fovea. Most importantly, I have produced a new model of visual word perception. It is the most complex (i.e., tending towards completeness) extant model of visual word recognition and provides a new avenue for testing hypotheses concerning word recognition.

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# Appendix A

# Published articles while at Edinburgh

## A.1 Foveational complexity in single word identification: Contralateral visual pathways are advantaged over ipsilateral pathways (Obregón and Shillcock, 2012)

The following paper has been published in Neuropsychologia. It is a refined version of my first experiment (Exp. I), namely that $\mathrm{Contralateral} > \mathrm{Ipsilateral}$ for single four-letter word recognition.

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# Foveational complexity in single word identification: Contralateral visual pathways are advantaged over ipsilateral pathways

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ABSTRACT

Recognition of a single word is an elemental task in innumerable cognitive psychology experiments, but involves unexpected complexity. We test a controversial claim that the human fovea is vertically divided, with each half projecting to either the contralateral or ipsilateral hemisphere, thereby influencing foveal word recognition. We report a novel haploscope task: the two halves of a four-letter word were briefly presented to the two eyes in a Both condition (st|ep)(st|ep), a Contralateral condition (st|__)(__|ep), or an Ipsilateral condition (__|ep)(st|__), all yielding the same single word percept (step). The Both condition yielded superior perceptual recognition, followed by the contralateral projection, then the ipsilateral projection. These results demonstrate that the structure of the fovea influences even the recognition of short, foveally presented words. Projecting different parts of the same word to different hemispheres involves unforeseen complexities and opportunities for optimizing hemispheric coordination.



## 1. Introduction

The lexical processing advantage of the right visual hemifield over the left visual hemifield is long established (Zaidel, Clarke, & Suyenobu, 1990); when a word falls to the right of fixation, it is directly projected to the left cerebral hemisphere (LH), which is typically dominant for language (Brysbaert, 1994; Melamed & Zaidel, 1993). It is generally claimed that the LH tends to specialise in processing expressive phonology (Coney, 2002), syntax (Caplan, Alpert, Waters, & Olivieri, 2000), and visual word-forms (Cohen, Jobert, Bihan, & Dehaene, 2004).

The human fovea has often been considered as a single concentration of receptors projecting directly and simultaneously to both hemispheres, but behavioural evidence has accumulated, along with computational and neuropsychological theorising, to suggest that the fovea shares the vertically divided structure of the rest of the retina (Brysbaert, 2004; Corballis & Trudel, 1993; Ellis & Brysbaert, 2010b; Lavidor & Walsh, 2004; Luo, Shan, Zhu, Weng, & He, 2011; McDonald & Shillcock, 2005; Monaghan, Shillcock, & McDonald, 2004; Shillcock, Roberts, Kreiner, & Obregón, 2010; Shillcock, Ellison, & Monaghan, 2000). Such foveal splitting implies that when a word is fixated, the part of the word to the right of fixation is initially projected directly to the LH, and the part to the left is initially projected to the right hemisphere (RH) for both eyes, even for visual field locations arbitrarily close to the fixation cue. Due to the compactness of the fovea, simple anatomical verification of this claim remains elusive (see Reinhard & Trauzettel-Klosinski, 2003, for evidence from impairment). The case rests on behavioural evidence. Thus, Lavidor, Hayes, Shillcock, and Ellis (2004) report differential effects of lexical neighbourhood based on statistics calculated separately for the left and right halves of centrally fixated six-letter words. Hsiao and Shillcock (2005) report that centrally fixated single Chinese characters with different left–right semantic/phonological structures result in naming-time differences that are predicted on the basis of foveal splitting. However, the claim has remained controversial. Jordan and Paterson (2009, 2010) marshal the evidence against it.

In the current paper we provide evidence for foveal splitting, and for further complexity in foveating words, based on the coordination of the hemifoveas across the two eyes when reading four-letter words.

Toosy et al. (2001) describe an fMRI study showing that monocular stimulation causes significantly greater and more extensive occipital lobe activation in the contralateral hemisphere: the right eye causes greater activation in the LH than does the left eye, and the left eye causes greater activation in the RH than does the right eye. Although each whole retina projects directly to both hemispheres, contralateral projections caused more activation than ipsilateral projections. Toosy et al. offer several potential contributing explanations: unique contralateral representation for a crescent of the temporal hemifield

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(Horton & Hocking, 1996); greater retinal ganglion cell density in the nasal retina (Perry & Cowey, 1985); a bias towards crossed fibres at the optic chiasm (Kupfer, Chumbley, & Downer, 1967) and the lateral geniculate nucleus (Chacko, 1948); organizational bias in the ocular dominance columns in V1 towards contralateral input (LeVay, Connolly, Houde, & Essen, 1985); and greater contralateral contribution to the activity of V1 cells with a binocular receptive field. Additionally, there is evidence for greater activation corresponding to the functionally dominant eye (Rombouts, Barkhof, Sprenger, Valk, & Scheltens, 1996). Thus, as well as the long-recognised contralateral and ipsilateral projections of the hemiretinas, there is a bias towards a contralateral projection at the level of the whole eye (see also Miki et al., 2001). Toosy et al. used full-field photic stimulation of each entire eye rather than just the fovea. Indeed, the monocular crescent exclusively available to each eye, as well as the blind spot, concern only non-foveal parts of the retina. The critical question remains whether Toosy et al.'s findings of advantaged contralateral projections apply to the processing of complex foveated targets.

In this paper we examine evidence for a functional contralateral bias specifically within the fovea. We predict a contralateral behavioural bias for foveal stimulation. The precise vertical splitting of the human fovea allows us to make detailed predictions for foveally presented lexical stimuli in conjointly and non-conjointly fixating eyes (Shillcock et al., 2010): for visual stimuli falling within the fovea for each eye, the two temporal visual hemifields (contralaterally projected) should be advantaged over the two nasal visual hemifields (ipsilaterally projected).

These effects are fundamental to visual processing, but they are subtle. We maximized the sensitivity of hypothesis testing in the following ways.

*Carving nature at its joints*: We have developed a new haploscope paradigm on the principle that making stimulus presentation adhere to the deepest anatomical and processing distinctions provides the clearest picture of the related behaviours.

*Maximizing processing pressure on participants*: This new paradigm challenges participants perceptually, by using very short, backward-masked presentations, matched to individual participants by pre-testing. The dependent variable is (within-participants) probability of correct word perception.

*Maximizing sensitivity of statistical testing*: We scored word reports according to a scale of correctness, for the dependent variable (probability of correct response). Further, we partialled out the variance of each participant with Linear Mixed Effects statistical regression modelling (Baayen, Davidson, & Bates, 2008).

In our novel paradigm, each half of each word was presented to one or both eyes, in a spatially correct order and for very short durations, so that the whole word was perceptually assembled across the two eyes in different ways; in each case, the whole word is perceived, but composed of input that is projected exclusively contralaterally, exclusively ipsilaterally, or both contralaterally and ipsilaterally.

Fig. 1 shows a schematic of how each of these three experiment conditions (lines a, b, c) was presented to the two eyes. The beginning bigram can be shown to either eye, but always to the left of where the eye is fixating. Similarly, the ending bigram can be shown to either eye, but always to the right of where the eye is fixating. Consequently, the beginning bigram is always projected to the right hemisphere, and the ending bigram is always projected to the left hemisphere (lines A, B and C in Fig. 1).

We hypothesized that if Contralateral and Ipsilateral conditions involved separate, direct projections to their respective cerebral hemispheres (see Fig. 1), there would be separable effects for each condition. The Null Hypothesis was that word recognition probability would not differ significantly between the Contralateral and Ipsilateral conditions. A significant difference would validate the claim that a vertically split fovea has critical processing implications; we predicted that the Contralateral condition would be more likely than the Ipsilateral condition to produce correct responses.

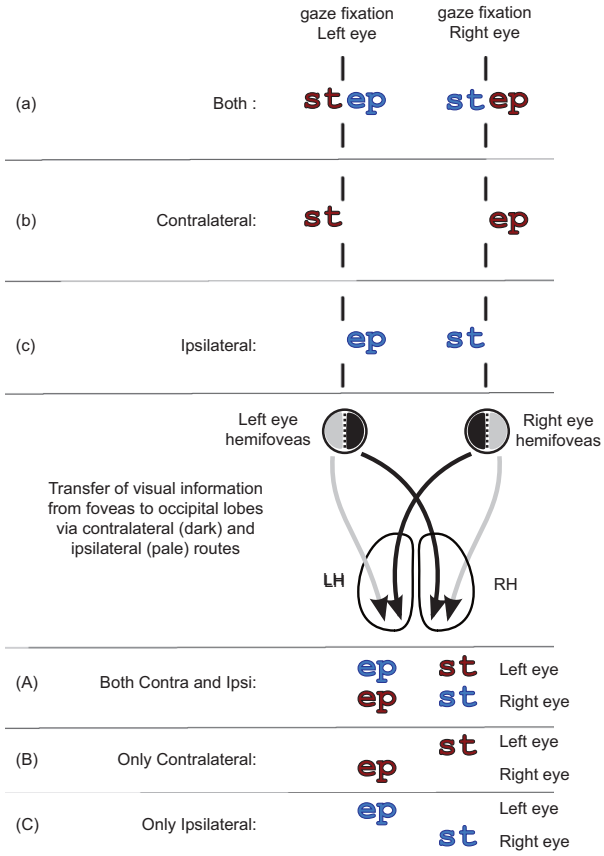


**Fig. 1.** Three stimulus conditions and their projection on to the four hemifoveas and the two hemispheres. The stimuli were presented as grey Courier New letters on a black background; bigrams are shown in different shades of grey in this diagram to make clear their contralateral (dark) or ipsilateral (light) pathways.

## 2. Method

### 2.1. Participants

Thirty students (aged 18–32 years, mean 21.4) gave informed consent to participate in the paid study approved by the Psychology Ethics Committee at the University of Edinburgh. All had normal or corrected to normal vision and were screened to ensure approximately equal visual acuity in each eye.

### 2.2. Apparatus

We used a mirror haploscope with four high-quality front-silvered mirrors and two large tubes (which acted as a septum) between the mirrors and two areas of a single screen on which the target items were presented. Mirrors and tubes were inside a matt black box and hidden from the participant.

### 2.3. Stimuli

The stimulus text was shown using a grey (RGB: 190,190,190) Bold Courier New 24 point font on a 15″ (32 cm × 24 cm) natural flat 0.25 pitch Vision Master Pro 413 IIYAMA monitor against a black background. Stimuli were pretested to ensure maximum visibility and minimum distortion through glare, as indicated by the shortest stimulus duration at which they were discernible. The display was connected to a dual head Matrox 450 graphics card operating at 70 Hz (1024 × 768 pixels), completely redrawing the screen every 14.28 ms.

Each participant saw 108 four-letter stimuli, generated from low and high frequency words taken from the MRC Psycholinguistic Database (Wilson, 1988), in Both, Contralateral and Ipsilateral experiment conditions (36 stimuli of each condition type, with 18 chosen from high frequency words and 18 chosen from low frequency words). On each trial, participants first saw a single broken vertical line defining a fixation region, resulting from the fusing of the separate monocular presentations of the same fixation stimulus. The letters for each eye were briefly presented to the left or right of this fixation cue. A backward-mask (consisting of a centred row of six '#' characters of the same font and a slightly darker grey as the stimuli letters) replaced the lexical stimulus in both eyes. Critically, the Contralateral condition (st|__)(__|ep) yields the same perception – a single word (step) – as the Ipsilateral (__|ep)(st|__) and Both (st|ep)(st|ep) conditions (see Fig. 1). A full four-letter word occupied 0.934 degrees of arc, falling wholly within the fovea.

### 2.4. Design

Within a repeated-measures paradigm, each participant saw one-third of the targets in each condition: Contralateral, Ipsilateral, and Both. Items from the three conditions were randomised and assigned to each of three Latin Square lists and included in an E-Prime (Psychological Software Tools, 2002) script. The targets were randomised within the first and second half of the experiment.

### 2.5. Procedure

The experiment was conducted in a quiet, darkened room. Participants looked through two apertures in the black box leading to the monitor 135 cm away and saw the contents of the two separate areas of the screen, unaware that each eye was receiving a different input.

The experiment was described as a perceptual recognition task in which letter strings would appear for a brief period of time. Participants were instructed to name any word or letters they saw. Pre-testing determined each participant's optimal presentation duration, to avoid floor and ceiling effects. This pretest consisted of 24 four-letter words (in the same order for all participants) in the three conditions (Both, Contralateral, and Ipsilateral) and at two presentation durations (28 and 57 ms). Correct word identifications determined a stimulus presentation duration of 14 or 28 ms for that participant in the experiment proper.

In the main part of the experiment, each participant was shown 108 four-letter words in one of the three experiment conditions at their assigned presentation duration. Participants were told to attend to the space in the middle of the fixation cue and to press – bi-manually and simultaneously – two buttons on a button box to start the trial when they felt ready. A random short delay (100–300 ms) followed the button press, designed to detach the visual perception from the button-pressing action. The two fixation cues were then replaced by the two parts of the target stimulus. After 14 or 28 ms, the stimulus was replaced with a backward-mask for the same amount of time. Participants then reported the perceived letters or word; all letters were recorded. The fixation lines then reappeared to both eyes for the next trial.

After the experiment, participants filled in a version of the Edinburgh Handedness Inventory (Oldfield, 1971) and answered three questions on eye preference. The experiment lasted 30 min, including a break midway.

## 3. Results

Data from 30 participants were analysed at the 14 ms presentation duration (12 females, 3 males) and at the 28 ms presentation duration (11 females, 4 males).

Because of variability in numbers of correct responses between participants, we used random effects modelling to analyse the data (Baayen et al., 2008) with the number of correctly identified letters as the dependent variable. That is, we modelled the differences between experimental conditions within each participant. This approach allowed us to better address the question, Is one condition identified more correctly than the other conditions? The analysis was conducted with the R statistical programming language (R Development Team, 2012), using the LanguageR and LME4 libraries (Baayen, 2011; Bates, Maechler, & Bolker, 2011).

We compared statistical models of increasing complexity until no further model could better account for the overall variance. We added variables into the linear model if they accounted for a significant amount of variability, as evidenced by a chi-squared comparison between the model without the new variable and the model with the new variable. One post hoc variable, *NextPressDelay* (defined for trial $n$, as the time between the onset of the fixation cue signalling trial $(n+1)$ and the participant's button-press initiating trial $(n+1)$), significantly improved the modelling ("NxtPrDel" in Table 1, Random Effects).

We used the Ipsilateral experiment condition as the base intercept case (line 0 in Table 1), which the model predicted to achieve 2.97 letters correct. As we expected, participants were most accurate in the Both condition (predicted score of 3.72 letters correct, $Z=9.36$, $p<0.001$, comparing lines 0 and 1 in the table), in which it was possible to superimpose the identical stimuli from the two eyes.

Critically, the model confirmed our prediction that the half-word stimuli presented in the Contralateral condition would be significantly more likely to be correctly identified than the half-word stimuli presented in the Ipsilateral condition. This outcome can be seen in the Z-score comparison between the Contralateral predicted value of 3.15 and the Ipsilateral predicted value of 2.97, $Z=2.36$, $p=0.0183$ (comparing lines 2 and 0, respectively, in the table).

Greater BNC written word frequency for the target facilitates participant ability to correctly identify letters. From line 3 in Table 1, a difference of one unit of the centred log(Frequency) term shows that participants improve their letter naming abilities from 2.97 (line 0, the Intercept) to 3.01, $Z=4.03$, $p<0.001$.

There were too few males to include Sex as a fixed-effect predictor for the model, but Sex did account for some variance, so it was left in the model as a Random Grouping term of Participant within Sex ("Sex/Participant" in Table 1, Random Effects).

There were no significant effects between the first and second halves of the experiment (implying no significant practice or fatigue effects). Furthermore, an analysis of the individual letter positions revealed no significant differences in correct identifications for each of the four letter positions

**Table 1**
LME model of the number of correctly identified letters, for Both, Contralateral and Ipsilateral experimental conditions.

| | Parameter | Model prediction | Model coefficient | Standard error | *Z* value |
|---|---|---|---|---|---|
| *Fixed effects* | | | | | |
| 0 | Ipsilateral | 2.9738 | 1.0898 | 0.0351 | 31.0500 |
| 1 | Both | 3.7157 | 0.2227 | 0.0238 | 9.3574*** |
| 2 | Contralateral | 3.1529 | 0.0585 | 0.0248 | 2.3589* |
| 3 | Log(Frequency) | 3.0144 | 0.0136 | 0.0034 | 4.0293*** |
| Groups | | Name | *N* | Variance | Std. dev. |
| *Random effects* | | | | | |
| Sex/participant | | (Intercept) | 30 | 0.0281 | 0.1675 |
| NxtPrDel\|Sex/Pp | | csrNextPressDelay | 2 | 0.0000 | 0.0048 |
| Sex | | (Intercept) | | 0.0000 | 0.0000 |
| NxtPrDel\|Sex | | csrNextPressDelay | | 0.0001 | 0.0078 |

0: Intercept case. Significance levels: *, $<0.05$; ***, $<0.001$.

(data not shown). In summary, responses followed the predicted pattern: *Both* ≫ *Contralateral* > *Ipsilateral*.

## 4. Discussion

We used a haploscope to manipulate the distribution of isolated-word orthographic input across the two eyes in a novel way, allowing us to explore the contributions of the different processing routes from fovea to cortex. We have shown a foveal processing advantage for the contralateral routes from retinal to cortical processing, extending the finding by Toosy et al. (2001) into the fovea and employing lexical stimuli.

Our data speak to the debate about whether – and if so, how – the vertical division of the retina into contralaterally projecting hemifields is continued into the fovea. The data show differential processing to the left and right of the presumed foveal centre (corresponding to the fixation point) for each eye. They are consistent with a theory of foveation in which the visual input is divided about the foveal centre and projected to contralateral hemispheres. They are not consistent with the homogeneous processing of the input in both the contralateral and ipsilateral experimental conditions, as would happen if all the foveal input were treated alike by being projected directly to both cortical hemispheres.

In classical optometry, the two eyes jointly fixate a point, projecting onto the centre of each fovea. This picture has been enriched over a long period of empirical investigation (e.g. Schreiber, Tweed, & Schor, 2006; Schreiber, Hillis, Filippini, Schor, & Banks, 2008; Wheatstone, 1838) but the subtleties of binocular fixation in reading are still unfolding (e.g. Shillcock et al., 2010). The experimenter faces a complex problem in knowing the continuous precise position of a fixated word with respect to the foveas, and in knowing the structural connectivity of the fovea itself (Ellis & Brysbaert, 2010a, 2010b; Jordan & Paterson, 2009, 2010). We have finessed these problems by using minimal fixation guides, centred in their respective circular frames in the haploscope, which we assume militates in favour of the two eyes centring their respective fixation guides and fusing them into a single percept; this procedure then guarantees the single fused percept of the briefly presented target word. In support of this assumption, our pilot testing showed that participants experience a blended percept – not an apparently normal word – at stimulus presentations longer than 80 ms.

The complexities of binocular foveation may be explored more comprehensively by computational modelling than by informal theorizing. Shillcock et al. (2010) present such modelling, showing a rich range of visual processing outcomes, depending on the strength of the contralateral advantage (demonstrated by the current data), anatomical variability in the precision of foveal splitting, the fixation disparity of the left and right eye on the word, and the prevalence of one eye's input over the other's after fusion. They suggest that readers use this range of processing outcomes adaptively to cope with the varying visual demands of reading.

In our view, it is not sufficient to abstract away from the anatomically based realities of the visual pathways and to map the informational nature of the stimuli (how many lexical neighbours a word has, what its frequency is, and so on) straight on to behavioural measures such as reaction time or perceptual accuracy. Psychologists have become increasingly interested in the detailed fixation behaviours involved in reading text, and these require increasingly detailed interpretations. Computational models incorporating this anatomical variation can provide detailed explanations that go qualitatively beyond the abstract statistical modelling of the data that has traditionally constituted psycholinguistic explanations. In addition, such an anatomically based approach challenges us to implement models that can represent readers, themselves with individual differences, flexibly applying different strategies and tactics to meet the changing processing demands of the reading task.

## 5. Conclusion

Binocular foveation is a complex process, departing substantially from the conjoint fixation of classic optometric theorizing, both in artificial tasks in which a word simply appears at fixation, and for normal, sustained text reading. The early stages of reading a four-letter word subtending less than one degree reveal significant processing discontinuities across the foveated stimulus, with an advantage for the contralateral pathways from each eye to the cortex. This complexity can be manipulated by the simple, automatic, peripheral mechanism of slightly crossing or uncrossing the eyes so as to change the relative fixation points of the two eyes, even within a single word, thereby changing the implications for the coordinated hemispheric processing of that word. Isolated word recognition – a pinnacle of higher cognition, and a workhorse of many cognitive psychology experimental paradigms – contains more adaptive complexity than we thought.

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## A.2 Binocular foveation in reading (Shillcock et al., 2010)

The following article discusses general theoretical issues in binocular foveation in reading. In particular, possible effects stemming from vertically split foveae are discussed, showing that a crossed- or uncrossed-fixation disparity effectively manipulates the text by either placing it beyond the horopter or in front of the horopter, respectively. My contribution revolves around the Contralateral pathways advantage that I found in Chapter **I**.

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# Binocular foveation in reading

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We present a theory of foveation in normal binocular reading. We consider the pervasive, nontrivial binocular fixation disparities (FDs) observed in reading and relate them to the computational problem of resolving retinal disparities in depth perception. We infer that the right eye's fixation being to the right of the left eye's in reading promotes binocular fusion in challenging conditions. We then show a different (nonfusional) processing advantage for the right eye's fixation being to the left of the left eye's in reading conditions in which binocular fusion is assured, by modeling the combined influence of foveal splitting, contralateral preference, ocular prevalence, and fixation disparity. This synthesis of anatomically grounded research in different aspects of visual processing produces a theory of foveation in reading that matches current data and makes testable predictions.

Our goal is to present a theory of foveation in binocular reading, explaining the variability in the positioning of the eyes to project the text across the two foveas. During normal reading, the left and right eyes frequently fixate different points in the line of text. The left eye may fixate to the left of the right eye, which is termed an *uncrossed* fixation disparity (FD), or to the right, termed a *crossed* FD. Several studies have suggested a pattern of predominantly conjoint or uncrossed FDs in reading (Blythe et al., 2006; Juhasz, Liversedge, White, & Rayner, 2006; Liversedge, White, Findlay, & Rayner, 2006), but two recent reports have revealed a substantial departure from this pattern (Nuthmann & Kliegl, 2009; Roberts, Shillcock, Kreiner, & Obregón, 2010). We present a theory of binocular foveation in reading grounded in research on stereopsis and on the structure of the visual pathways between the fovea and the cortex. The theory has three central premises: that individuals unconsciously manipulate their FD in response to viewing conditions to facilitate fusion, that uncrossed FDs facilitate binocular fusion more than crossed FDs do, and that crossed FDs facilitate postfusional processing more than uncrossed FDs do. These tenets lead to the conclusions that, when reading conditions militate against binocular fusion, readers tend to opt for uncrossed FDs and that, when binocular fusion is unproblematic, readers tend to opt for crossed FDs.

We begin with a detailed description of the variations in FD in reading. We then consider theoretical explanations of disconjugacy[1] during saccades (which results in FD) and conclude that some additional explanation is required to account for the range of FDs reported between reading studies. Our explanation proceeds from the observation that the computational consequences of FD resemble the correspondence problem encountered in depth perception: Both involve a directional noncorrespondence between the images on the respective retinas, mediated by position with respect to the horopter. From our review of the stereopsis literature, we conclude that binocular fusion in reading is more easily achieved during uncrossed FDs than during crossed FDs and that viewing conditions such as luminance, blur, font size, and viewing distance prompt changes in FD.

We complete our explanation by providing a rationale for the large number of crossed FDs reported by Nuthmann and Kliegl (2009) and by Roberts et al. (2010). We describe a high-level model of the visual pathways from fovea to cortex. The model shows that the combination of known aspects of the visual system, such as ocular prevalence and bias for contralateral over ipsilateral projection, result in a robust processing advantage for crossed FDs. This finding leads to our overall conclusion that crossed FDs are advantageous for readers when fusion is unproblematic.

## Fixation Disparity

**FD in reading**. Binocular studies of reading, both of children and adults, date back many decades but have become a recent focus of research due to the greater availability of binocular eyetrackers (Bassou, Granié, Pugh, & Morucci, 1992; Blythe et al., 2006; Clark, 1935; Heller & Radach, 1999; Hendriks, 1992, 1996; Hendriks, Kolk, & van der Wildt, 1991; Juhasz et al., 2006; Kliegl, Grabner, Rolfs, & Engbert, 2004; Liversedge et al., 2006; Nuthmann & Kliegl, 2009; Roberts et al., 2010; Schmidt, 1917; Taylor, 1966; Ygge & Jacobson, 1994).

The data on direction of FD vary substantially across recent studies, regarding the relative proportions of crossed, uncrossed, and conjoint fixations (see Table 1); this variability is the primary *explicandum* for a theory of binocular foveation. In addition to the data in Table 1, Yen and Radach (2007) reported more uncrossed than crossed FDs, but no precise numbers; Heller and Radach (1999) did not state the direction of the FDs. Liversedge et al. (2006) stated

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**Table 1**
**Percentages of Different Types of Fixation Disparity From Recent Studies**

| Study | Conjoint | Crossed | Uncrossed |
|---|---|---|---|
| Liversedge et al. (2006) | 53 | 8 | 39 |
| Juhasz et al. (2006) | 55 | 18 | 27 |
| Blythe et al. (2006) (adult data) | 48 | 12 | 40 |
| " " (child data) | 39 | 24 | 37 |
| Nuthmann & Kliegl (2009) | 58 | 39 | 3 |
| Roberts et al. (2010) | 14.5 | 85 | 0.5 |

"At present, it is not clear why this difference [between crossed and uncrossed] between the present data and those of Kliegl et al. [2006] occurred. Clearly, further research is required to more fully understand this interesting difference" (note 6, p. 2368; see also Kirkby, Webster, Blythe, & Liversedge, 2008, p. 747). Nuthmann and Kliegl (2009) concluded that "the marked differences across studies suggest that not only individual differences and developmental aspects but also factors related to the experimental setting determine whether the adopted fixation disparity is predominantly crossed or uncrossed" (p. 22) and listed several candidate explanations: eyetracker technology, calibration procedure,[2] saccade detection method, viewing distance, visual angle per letter, head movement constraint, color of text and background, room illumination, and language used. We may add to this list the issue of sentential versus paragraph stimulus materials.[3]

The data cited in Table 1 were acquired in different experimental conditions that are relevant to understanding FD in reading. Figure 1 graphs the variation in FD in reading studies and demonstrates the relation between the proportions of the three fixation types (crossed, uncrossed, conjoint) and the size of the angle subtended by a single character on the retina.[4] There are only substantial proportions of uncrossed FDs in the studies in which the font subtends a smaller angle on the retina; coincidentally, these are the studies using a dual Purkinje display, in which bright letters are presented on a black background in a darkened room. In contrast, the studies showing more substantial proportions of crossed FDs use dark text on light backgrounds in normal lighting conditions with larger text.

Liversedge et al. (2006, Figure 2) showed the proportions of uncrossed FDs and conjoint fixations in approximately complementary distribution across the line of text. Nuthmann and Kliegl (2009) reported a complementarity in the proportions of conjoint fixations and crossed FDs. Thus, different data sets tend to contain complementary proportions of conjoint fixations and one directional FD, with the other direction of FD relatively marginalized. We have analyzed this situation in Figure 2 by taking the estimated mean FD of each data set (it has to be estimated, because FDs of less than one character are standardly taken to be conjoint) and by situating each mean along the *x*-axis. Each vertical line represents one of the data sets in Table 1, identified by the initial of the first author of the

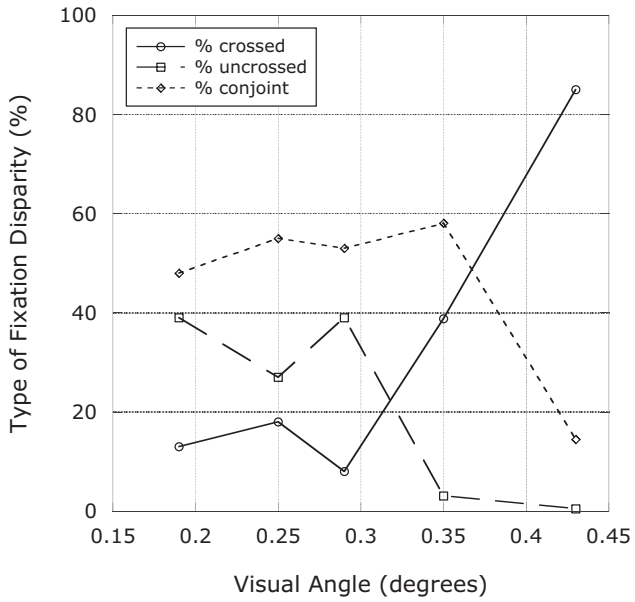



**Figure 1. Meta-study of published data comparing percentages of crossed, uncrossed, and conjoint FDs with retinal angle subtended by a single monospaced letter. From smallest visual angle on the left, data sets are from Blythe et al. (2006), Juhasz et al. (2006), Liversedge et al. (2006), and Nuthmann and Kliegl (2009), and from a subset of 14 from our present English text-reading corpus data. Note that there are procedural differences between the five studies (see text for details); one such difference is that the Nuthmann and Kliegl data were acquired using binocular calibration.**

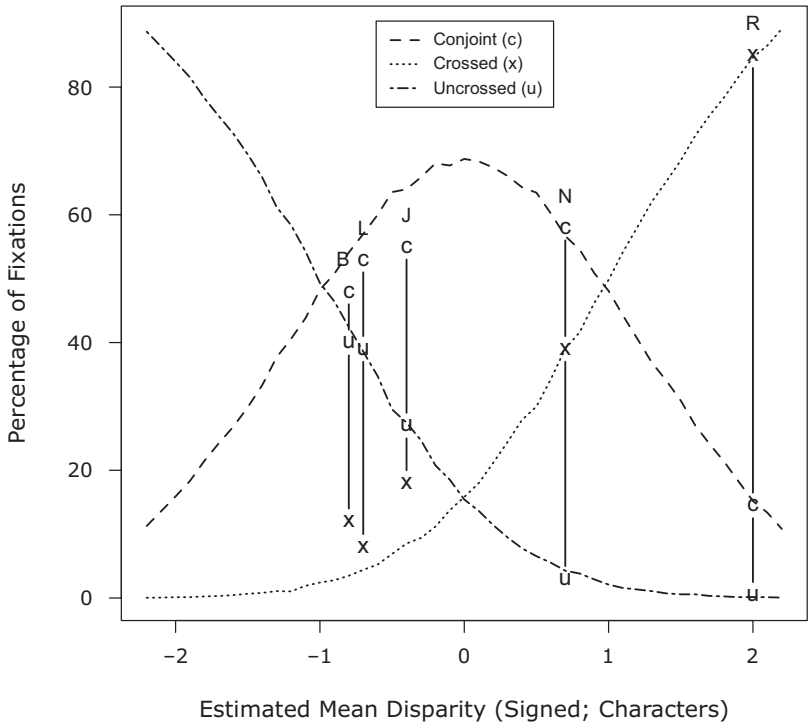



**Figure 2. Proportions of uncrossed, conjoint, and crossed fixation disparity (FD) for estimated overall mean disparities greater than −2 and less than 2 and assumed *SD*s of 1, where FD is L–R, in characters. Vertical lines show the best-fitting means for the proportions reported in the studies summarized in Table 1; the initials B, L, J, N, and R refer to the particular data sets. The estimated means themselves are less important than is the demonstration that the varying percentages of the fixation subtypes (conjoint, crossed, uncrossed) in the reported data sets may be seen as the outcome of partially overlapping distributions of those subtypes, yielding different mean FDs overall for those data sets. The mean FD overall for a data set, and its sign, must then be explained. See the text for this explanation.**

respective article. The differing proportions of disparity subtypes within each data set may be seen as the intersection of partially overlapping distributions of the three subtypes. Thus, change in the mean FD appears as complementary variation between the dominant FD (crossed or uncrossed within a particular data set) and conjointness, with the nondominant FD appearing relatively unaffected; for instance, the Nuthmann and Kliegl data ("N" in Figure 2) have an estimated overall FD of less than one character and are composed of 58% conjoint fixations and 39% crossed fixations, so that any small variation about the overall mean FD results in larger complementary variation between the conjoint and crossed categories and in smaller variation in the percentage of uncrossed fixations. In the rest of the present article, we address the question of why any FD happens and why it occurs in one or other direction (crossed or uncrossed). Figure 2 demonstrates that the reported data sets can all coexist as accurate depictions of binocular fixation behavior within orderly relations between the equally legitimate conjoint, crossed, and uncrossed subtypes.

In summary, FD is pervasive in reading, but is variable, with the basic data on the direction of the FD and its role in reading a central research question. Below, we will pursue the hypothesis that these data sets are mutually compatible; they do not reflect error in the system, but are strategic responses to the stimulus and the task. We begin with a review of the literature on FD in nonreading tasks.

**FD in nonreading tasks**. Several nonreading studies have shown substantial disconjugacy in binocular saccades along with FD. Enright (1998) reported an experiment in which binocular recordings were made of 3 participants' repeated saccades between two points (20 or 26 cm away), requiring version, vergence, and isovergence movements. The chief finding was of a binocularly unbalanced saccade that resulted in good foveation of the target by one or other eye, with substantial deviation of the partner eye, which then required an asymmetric vergence movement. This behavior still occurred in the isovergence case (a task more comparable, in terms of depth, to reading), although the deviation of the initially less accurate eye was smaller (see Enright, 1998, Figure 10). There were no clear conclusions regarding direction and eccentricity of the target point from each eye. Cornell, Macdougall, Predebon, and Curthoys (2003) reported data from a task requiring symmetrical vergence movements in natural conditions.

Participants produced significant underconvergence for near fixations (52.5, 30, and 21 cm, comparable with reading distances) and overconvergence for far fixations. For the near fixations, 85% of errors were from −30 to +120 arc min. Comparing the situation in these vergence tasks with the crossed/uncrossed FDs in reading, underconvergence produces an uncrossed FD and overconvergence produces a crossed FD.[5] We conclude from these two studies that binocular FD—as opposed to precisely conjoint fixations—often happens in three-dimensional nonreading tasks without incurring diplopia; Cornell et al. remarked specifically on the absence of diplopia.

It is worth noting that, in real-world viewing, the great majority of objects do not fall on the horopter, the circle on which the fixation point sits. For instance, when we fixate an object on a crowded desk, there are typically objects both in front of and beyond the horopter; such objects are not, therefore, projected to corresponding points on the two retinas, but the relevant images still need to be coordinated (by binocular fusion or suppression). Saccades requiring a vergence change are more representative of real-world viewing than are the persistent near-isovergent saccades required in reading.

In other studies of binocular coordination in nonreading tasks, the saccades have been exclusively isovergent; these tasks are, therefore, more comparable with reading. Collewijn, Erkelens, and Steinman (1988) reported using a scleral sensor coil, in which 3 participants repeatedly fixated between two isovergent LEDs in a dimly lit room. They reported a "binocular fixation error of about 0.3º in the divergent direction" (p. 168; i.e., uncrossed FDs, which formed the majority). They also reported the typical undershooting seen previously in the literature. Fioravanti, Inchingolo, Pensiero, and Spanio (1995) used an infrared limbus-tracking system to study binocular saccades within an isovergent circle of LEDs and found uncrossed FDs for adults and for 11- to 13-year-old children but found crossed FDs for 5- to 10-year-old children. Yang and Kapoula (2003) used an oculometer (Bach, Bouis, & Fischer, 1983) to study saccades made to LEDs in near and far isovergent circles by children and adults and found substantial FDs in the uncrossed direction (Figure 1, p. 556), with greater disconjugacy in children and for near targets. Other articles have suggested the same conclusion; for instance, Cornell et al. (2003) cited Malinov, Epelboim, Herst, and Steinman (2000), calculating vergence errors ranging from 1.5º to 3º. (See also Collewijn, Erkelens, & Steinman, 1995, and Erkelens, Steinman, & Collewijn, 1989, who reported errors of up to 6º.)

The first conclusion from these binocular-nonreading studies is that immediate or sustained, precise conjoint foveation does not always happen and is not always necessary; "saccades are not temporally and spatially conjugate as has often been assumed" (Kirkby et al., 2008). No diplopia was reported in the studies reported above, although Yang and Kapoula (2003) said "coordination is particularly poor at near [distances] and could compromise single binocular vision" (p. 554). Cornell et al. (2003) argued that individuals are tolerant of physiological diplopia in normal, free-viewing situations in which there is head movement and multiple fixations in a complex visual environment. Binocular fusion is robust when there are large objects in the visual field (Schor & Wood, 1983; Tyler, 2004, p. 21), and such stimuli, once fused, are resistant to diplopia. These data contrast with the very strict conditions on binocular fusion, as in the classic statement of Panum's fusional area (~15 arc min), found when demanding experimental conditions are imposed (e.g., no head movement and the brief, single presentation of impoverished stimuli). The second conclusion from these studies is that uncrossed (divergent) FDs are widely found in nonreading tasks.

What explanations have been offered for disconjugacy in saccades and for binocular FD? Yang and Kapoula (2003) evaluated two theoretical possibilities: that they may result from unequal cortical signals to each eye or from asymmetry in the oculomotor musculature. They drew two principal conclusions: First, even if, as required by Hering's law of equal innervation, a single signal is generated by the cortex to move the eyes, it is clear that the signal has diverged along different pathways by the time it reaches the eyes. This process of fine tuning is less evident in children and must be learned: "Learning and adaptation are needed for the fine tuning of motor commands for each eye to enable normal quality of binocular coordination in adults" (p. 559). Although such fine tuning might appear to be strong evidence against Hering's law, they acknowledge the possibility that "it is basically true but imperfect" (Ibid.). Second, they show that the hypothesis that saccadic disconjugacy is caused by muscular asymmetry is incompatible, both with their own behavioral data and with the known facts of physiological development. This hypothesis is based on the fact that the lateral rectus muscle (controlling *ab*duction, i.e., away from the nose) produces more acceleration in the saccade than does the medial rectus muscle (controlling *ad*duction, i.e., toward the nose), so that the two eyes diverge. They concluded that "the distance-dependent disconjugacy of the amplitude of saccades is most likely due to immature cortical or subcortical control of saccade signals when the eyes are converged than to muscular difference between the two eyes" (p. 560).

The variation in FD that has been reported in different studies of reading supports the conclusion that muscular asymmetry is not its primary cause. Muscular asymmetry (specifically, stronger *external* recti) would seem consonant with a pattern of largely uncrossed FDs but not with the opposite pattern reported by Nuthmann and Kliegl (2009). The hypothesis presented here builds on Yang and Kapoula's (2003) assertion that "the binocular coordination of saccades is not built-in, but is a process developing through visual experience and learning" (p. 560). This claim implies that experienced readers may exercise a degree of independent control over their two eyes. We posit that they may use that control to optimize their FD for the reading conditions at hand. The flexibility of the system is apparent in data from a heterogeneous group of amblyopic adults reported by Conner, Odom, Schwartz, and Mendola (2007), who suggested that radical pathological binocular FD may lead to the system suppressing some fine-grained

central input, while maintaining processing in peripheral vision. Exactly how the adaptiveness that we propose for binocular FD is realized is a matter for further research.

In conclusion, noncorrespondence in much of the image is unavoidable in the three-dimensional world: Substantial FDs have been widely observed in a range of viewing tasks, and we should expect them in reading, with no noticeable diplopia. The direction of the FD is frequently uncrossed, but no principled explanation of the direction of the FD has emerged beyond those based on error and hypometric inertia (see, e.g., Cornell et al., 2003). We now show how FDs in reading entail some of the same computational issues identified in depth perception.

## FD, Retinal Disparities (RDs), and Depth Perception

Depth perception enables us to negotiate the visual world and perceive the solidity of objects. There is a critical difference between perceiving objects behind and in front of the horizontal horopter (on which all points, including the binocular fixation point, produce single vision and project to corresponding points on the retinas), all in a single binocular perception of the world. A conjointly fixated point is projected onto the fovea of the left and right eyes. When projected onto the retina, objects beyond the horopter give rise to uncrossed RDs (defined below). Objects in front of that plane of focus give rise to crossed RDs. This difference is a qualitative one in terms of the sign of the relative warping of the images on the two retinas with respect to the relevant corresponding points (see, e.g., Hershenson, 1999, p. 36, for the textbook description of both types of RD; cf. Blakemore, 1969; Collewijn, Steinman, Erkelens, & Regan, 1991). Thus, if the viewer raises his or her finger in front of a distant tree, fixating on the finger produces an uncrossed disparity for the tree; the left eye (LE) sees tree–finger (from left to right across the field), the right eye (RE) sees finger–tree, and overlaying the two monocular images produces an uncrossed double image of the tree: tree–finger–tree. This case is "uncrossed," because the tree is to the left in the LE and to the right in the RE. In the crossed case, the viewer fixates on the tree, the LE sees tree–finger, and the RE sees finger–tree, which produces the crossed double image finger–tree–finger. This case is "crossed," because the finger is to the right in the LE and to the left in the RE. This is the definition of *relative disparity*, in which an object off the horopter is seen in depth relative to the horopter and the viewer.

Figure 3 illustrates how a crossed FD generates the signed directional consequences of an uncrossed RD. Figure 3A shows that in an uncrossed FD in reading, the *o* in *fox* in the LE occurs to the right of the *o* in *fox* in the RE (equivalent to a crossed RD). Conversely, in Figure 3B, in a crossed FD, the *o* in *fox* in the LE occurs to the left of the *o* in *fox* in the RE (an uncrossed RD).

In the (recent, small) binocular reading literature, the term *FD* is used to refer to the distance between the two fixation points on the text. We have referred above, to the (older, larger) stereopsis literature, in which an RD describes the relative placement of images on the two retinas.[6] There is an unfortunate use of the same terms "crossed" and "uncrossed" in the binocular-reading and stereopsis literatures, respectively, to refer to the relationship between the two eyes' fixation points on the text and to directional noncorrespondences between the images on the retinas; in making an argument relevant to both

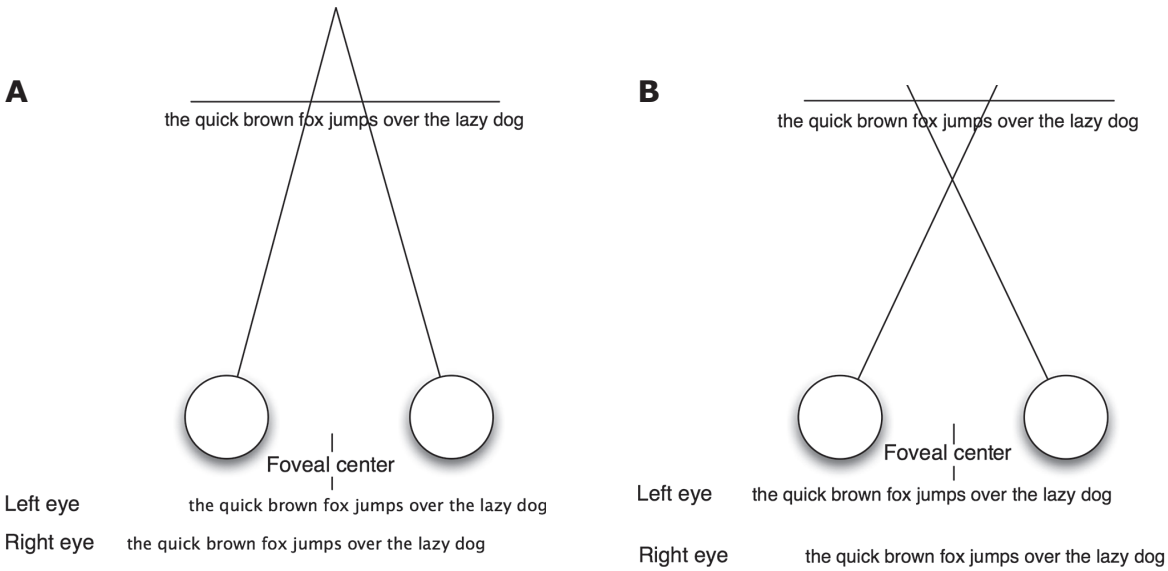



**Figure 3. Fixation disparity (FD) produces noncorresponding images at the two retinas. (A) An uncrossed FD in reading, equivalent to a crossed retinal disparity (RD). (B) A crossed FD, equivalent to an uncrossed RD. The disparity *X* between the two images is signed, + or −, and is analogous to that observed in depth perception for objects not on the horopter. The uncrossed FD effectively brings the text in front of the horopter, and the crossed FD sends it behind the horopter (as defined by the point of intersection of the two lines of sight). The sign has implications for the processing domain that achieves binocular fusion. See the text for details.**

literatures, we are explicit throughout in distinguishing FDs from RDs. (This distinction naturally applies across viewing tasks other than reading.)

Thus, the binocular-reading research community understand a "crossed disparity" to refer to the right eye's fixation point on the text being to the left of the left eye's fixation point, and they have not been concerned with the precise implications for the location of the images on the retina. In contrast, the rest of the vision-science community understands the older usage of "crossed disparity" as referring to the difference between the images on the retinas associated with a midline object situated between the viewer and the intersection of the lines of sight from the two eyes (see above); the vision science community has typically been less interested in situations in which the two eyes do not, in principle, fixate the same point in the world and has usually seen this as "vergence error." In the present article, we have tried to explore the relation between these two situations in terms accessible to both research communities. For future reference, *crossed fixation points on the page ≡ uncrossed disparities on the retina ≡ over convergence ≡ esodisparity* and *uncrossed fixation points on the page ≡ crossed disparities on the retina ≡ underconvergence ≡ exodisparity*.

To achieve binocular perception, the cortex needs to perform qualitatively different coordinations of the relevant parts of the images on the retinas in crossed and uncrossed RDs. It should also be clear that fusion is a more complex computation than simple geometric translation. Most real-world scenes require a constant interplay between the processing of crossed and uncrossed RDs as objects are fixated in near and far space, and a single binocular percept is created of the whole visual field; these opposite RDs are defined with respect to each other and are typically copresent.[7] However, it is shown below that different processing considerations attach to the domain in front of the horopter and to the domain behind it.

Normally, we formalize depth perception as a situation in which we fixate conjointly on one object and in which a second object, either in front of or behind the horopter, is seen in depth; the second object creates a relative disparity at the two retinas. The problem for the visual system is the central one of coordinating the two noncorresponding whole retinal images. The horopter, created by the current fixation point, is essential to understanding depth processing: Regions off the horopter are perceived as having depth with respect to the horopter and the viewer. The relative disparity of an object off the horopter is quantified as the difference between its absolute disparity and the absolute disparity of the fixation on the horopter (where absolute disparity is the angle subtended at the object by the lines of sight from the two eyes). Note, first, that there does not need to be an actual object fixated on the horopter for absolute disparity to obtain for objects off of the horopter (and, indeed, the two lines of sight may not actually cross if there is vertical disparity; Collewijn et al., 1991, p. 122). Note, second, that, although absolute disparity (the angle between the two lines of sight) provides little information for depth perception in the presence of other cues, absolute disparity information is always available, as is evidenced by the central ability of the eyes to converge on an isolated stimulus (cf. Howard & Rogers, 2002, pp. 151–152); indeed binocular neurons in (macaque) V1 select for absolute disparity and not for relative disparity (Cumming & Parker, 1999).

Consider the following range of circumstances: When there are two objects at different distances from the horopter, their relative disparities may be defined with respect to each other and independent of ocular vergence and conjugate eye movements, or they may be defined with respect to the horopter. When there is a single object off the horopter, its relative disparity may be calculated with respect to a fixated object (on the horopter); we will see, below, that it is critical whether the object is in front of or beyond the horopter. When there is a single fixation plane, with no other point of reference, there is only an absolute disparity, with little or no depth perception generated on the basis of this absolute disparity. Finally, when there is an FD (the two eyes not fixating conjointly), such as in our reading case, and substantially a single fixation plane with no other point of reference, we still have an absolute disparity, but a virtual fixation point in which the lines of sight intersect in front of or behind the text. The two eyes receive overall disparate (Howard & Rogers, 1995, p. 243) images of the text which must still be coordinated. We have seen that this overall disparity is signed (the crossed or uncrossed cases are qualitatively and directionally different). Although this overall disparity does not reveal anything about the structure of the visual scene (indeed, in the reading case, the text is substantially all at the same depth), we can still generalize from the other cases of the coordination of disparate images. Note, again, that the coordination of the two images is always a more complex task than simple geometric translation: In every fixation, the full panoply of depth mechanisms and processes is available.[8] As demonstrated above, the central factor in the range of cases of depth perception considered is the location of the horopter; we will review, below, the evidence for the critical signed distinction between object location in front of and beyond the horopter.

The central point we make here is that the computational consequences of depth perception generalize to the processing of FD in reading. The visual system is required to coordinate noncorresponding images on the two retinas, with a critical signed difference in direction. In an uncrossed FD, the principal visual axes from the reader's eyes meet behind the page or screen; in the crossed case they meet in front.

The essence of FDs in reading is that an uncrossed FD places the text within the horopter and that a crossed FD places it beyond the horopter (respectively defined by the virtual and real crossing of the lines of sight). This formal generalization from stereopsis to reading means that the processing of FD in reading inherits the processing distinctions reported in stereopsis regarding depth relations in front of and beyond the horopter.

Studies of depth perception suggest that the brain solves the two computational problems posed by positive and negative RDs relatively independently. The initial case was made by Richards (1970, 1971a, 1971b),

who presented psychophysical and clinical evidence of separate detectors for crossed and uncrossed RDs. Later research supports this claim (Birch & Foley, 1979; DeAngelis, 2000; Foley, 1976; Foley & Richards, 1978; Poggio & Fischer, 1977; Regan & Spekreijse, 1970). Below, we review studies comparing crossed with uncrossed RDs, further supporting the conclusion that there are at least[9] two anatomically and functionally dissociable processing domains corresponding to the two types of RD.[10]

In summary, the computational problem faced by the reader of coordinating noncorresponding retinal images resembles the problem of perceiving objects in the real world in depth. In depth perception, the two aspects of the problem are solved in different (crossed and uncrossed RD) processing domains, although these processing domains are intimately connected and complementary aspects of depth perception. However, the relationship between crossed and uncrossed RDs is not symmetric, as we see below when we review a substantial literature showing that crossed RDs offer a number of general advantages in nonreading tasks. Further below, we explore how different viewing conditions may offer differential advantages to crossed and uncrossed FDs in reading.

**Crossed RDs Are Prioritized in Nonreading Tasks**

Mustillo (1985) discussed evidence from studies in a range of paradigms—psychophysics, eye movements, human development, clinical cases, human electrophysiological data, animal behavior, and neurophysiology—and concluded that crossed RDs are processed more readily and more efficiently than are uncrossed RDs. We update Mustillo's review and develop the relevant parts toward the issue of FDs in reading.

*Stereofusion*. There is a clear advantage of crossed RDs in recruiting visual information for fusion. Dengler and Kommerell (1993) investigated the limits of RD in a task requiring participants to report depth perception in relation to a pair of 3º discs presented, respectively, to the fovea of one eye and the periphery of the other. They showed that crossed RDs could be processed at larger angles of separation than could uncrossed RDs. Woo and Sillanpaa (1979) also reported that the threshold for stereopsis was lower in crossed than in uncrossed RDs. This difference reflects the real-world constraint that an object's images in the two eyes are more disparate when the object is closer rather than when it is farther away. This finding replicates the earlier one of Richards and Foley (1971), who showed some participants being able to process as much as 16º of a crossed RD (up to four times greater than uncrossed RDs; see also Grabowska, 1983; Lasley, Kivlin, Rich, & Flynn, 1982; Schor & Wood, 1983). These data speak directly to the flexibility of the visual system in maintaining fusion in relatively natural scenes, despite large RDs.

There is also a temporal dimension to stereofusion. When a lag is introduced between the presentation of the stimuli to each eye, depth is perceived more robustly during crossed RDs than during uncrossed RDs (Godek & Lawson, 1973; Ogle, 1963). Similarly, when RD information is only briefly available, participants process crossed RDs at shorter presentations than they do uncrossed RDs (Beverley & Regan, 1974; Regan & Beverley, 1973a, 1973b).

In summary, the greater effective range of stereofusion in crossed RDs (i.e., uncrossed FDs) implies that uncrossed FDs are more effectively and efficiently fused (although the observed data from reading would rarely seem to approach the limits of fusion reported by Richards & Foley, 1971).

*Stereoacuity*. Stereoacuity has been generally reported as being higher in crossed RDs than in uncrossed RDs in depth perception tasks (e.g., Lam, Tse, Choy, & Chung, 2002), although some researchers have failed to find a difference (see Howard & Rogers, 1995, p. 166, for a review). When fine distinctions are required in stereofusion, uncrossed FDs may, therefore, be more appropriate.

*RD and the visual field*. Richards and Regan (1973) showed that there are different stereopsis field maps for crossed and uncrossed RDs, with the former being larger than the latter, extending both above and below the fovea, and being substantially biased toward the right visual field (RVF); the field map for the uncrossed RDs is relatively small (and is also biased toward the RVF).

*Stereoanomaly*. Richards (1970) reported deficient stereopsis in some 30% of the population, with greater impairment in the processing domain responsible for uncrossed RDs (and, therefore, crossed FDs; see also Richards, 1971a). This asymmetry may reflect a general advantage for crossed RDs in stereofusion.

*Developmental priority*. The processing of both crossed and uncrossed RDs is achieved in the first year of life, but crossed RDs appear to have developmental priority (Birch, Gwiazda, & Held, 1982; Held, Birch, & Gwiazda, 1980).

*Sex differences*. A sex difference exists in the perception of random-dot stereograms: Both males and females tend to be more sensitive to crossed RDs, with this pattern being more marked in females—that is, they have a lower threshold for perceiving depth in a random-dot stereogram in the crossed case (Zaroff, Knutelska, & Frumkes, 2003).

We have seen that there is a clear asymmetry between the processing associated with crossed and uncrossed RDs, with the former facilitating fusion more than the latter. This conclusion suggests that crossed RDs (equivalent to uncrossed FDs) should be preferred when stimulus conditions are such as to jeopardize binocular fusion; as shown below, uncrossed FDs will also perforce occur in very close viewing at the limits of convergence. We assume that binocular fusion difficulty is at least partly defined as resulting from stimulus conditions that militate against solving the correspondence problem (i.e., coordinating the images from the two eyes): These visual stimulus conditions will include low contrast, absence of large distinct areas and contours, and a low figure-to-ground ratio. We have seen that uncrossed FDs in reading studies are more associated with bright text on a dark background, subtending a small retinal angle in dark conditions (Figure 1). However, it does not necessarily follow that these uncrossed FDs are a *consequence* of fusion difficulty. Is

there any experimental evidence that viewing conditions militating against binocular fusion can precipitate crossed RDs? Several studies support this conclusion.

Jaschinski-Kruza (1994) reported that reduced luminance and increased target blur cause a shift to uncrossed FDs, where the fixation target was a block of text (see, also, Pickwell, Jenkins, & Yekta, 1987); this change in disparity was up to 20 arc min in participants whose angle of resting vergence in dark conditions (i.e., *dark vergence*) was smaller (i.e., more distant) than was the viewing distance used (Jaschinski, 1997). Richards (1973) reported the case of several stereo-anomalous observers, for whom the sign of their perceived depth confusion (mistaking zero-disparity for crossed or uncrossed RDs) was reversed in disparity when the stimuli changed from dark bars on a light background to light bars on a dark background. We are currently exploring a single case of a normal reader's changes from crossed to uncrossed FDs in reading when room illumination changes from normal to low level, with black text on a white screen (Shillcock, Roberts, Kreiner, & Mac Cumhaill, 2007).[11] Thus, uncrossed FDs (crossed RDs) are not just associated with more robust fusion; there are grounds for believing that the relevant conditions can precipitate uncrossed FDs.

In overall summary, we have seen a general preference for crossed RDs over uncrossed RDs (uncrossed FDs over crossed FDs) in nonreading tasks, where fusion is more or less directly implicated. We might, therefore, expect uncrossed FDs to predominate in reading. However, the studies listed in Table 1 do not unambiguously confirm this prediction. In fact, all the studies reported some percentage of crossed FDs and, in some cases, this percentage is greater than for uncrossed FDs. Next, we explore the roles of uncrossed RDs or crossed FDs in nonreading tasks in the light of the previous review, before considering why FDs in reading are not universally uncrossed.

## Advantages of Uncrossed RDs in Nonreading Tasks

We have shown that crossed RDs (uncrossed FDs) are advantageous in several different ways. However these advantages are not exclusive, as shown below: Uncrossed RDs (crossed FDs) have at least some advantages over crossed RDs (uncrossed FDs), although these advantages may be relatively minor in the case of reading.

*Asthenopia*. Near-vision tasks tend to generate uncrossed FDs when the convergence response is weak and vergence tends toward the (distant) resting position; as a result, crossed FDs and aligned binocular fixations as a group are associated with less asthenopia (visual stress caused by near-vision tasks) than are uncrossed FDs (Jenkins, Pickwell, & Yekta, 1989; Pickwell, 1989, 1991; see, also, Jainta & Jaschinski, 2002; Jaschinski, 1997, 2001), although there are individual differences (Pickwell, 1989). Further, eye strain in close work is stronger in those subjects with marked changes in FD in the uncrossed direction due to near vision (Jaschinski, 2002). Uncrossed FDs appear to be more muscularly onerous for the visual system than are crossed FDs (although there may be an issue of cause and effect if uncrossed FDs are a response to other problems for binocular fusion).

*Temporal aspects of RD processing*. There is an initial bias toward uncrossed RDs. Goutcher and Mamassian (2006) recorded crossed or uncrossed RD perceptual reports over time, as participants stared at a stereoscopically bistable stimulus. They found an initial preference for uncrossed RDs, followed by alternating perceptions, and concluded that there seem to be two distinct phases in stereo matching—one early and the other sustained.

An initial preference for crossed FDs was also reported by Setter and Norman (2006) in a series of nonreading experiments in which random-dot stereograms were presented at RDs that corresponded to being in front of, on, or behind the screen. The authors reported that their 7 participants first fixated the screen briefly (never less than 50 msec, the minimal time required to perceive a random-dot stereogram; Julesz, 1964; Tyler, 1991) and then converged, so that the principal lines of sight crossed in front of the screen. Furthermore, this point of (crossed) convergence was closer to the observer for crossed retinal images, was farthest away from the observer for uncrossed retinal images, and was at an intermediate distance when the image disparity was zero. The authors discussed their results in terms of the system reverting to the resting point of vergence (cf. Jainta & Jaschinski, 2002; Jaschinski, Bröde, & Griefahn, 1999; Jaschinski, Koitcheva, & Heuer, 1998; Jaschinski-Kruza, 1994).

*Viewing distance*. The disparity limit for crossed RDs is unaffected by angular size, but, for uncrossed RDs, it tends to increase with increasing convergence (decreasing fixation distance; Richards, 1971b). Furthermore, Richards and Foley (1971) found that stereoacuity increased with accommodation for uncrossed RDs, but not for crossed RDs. Uncrossed RDs, thus, seem more flexible for near viewing.

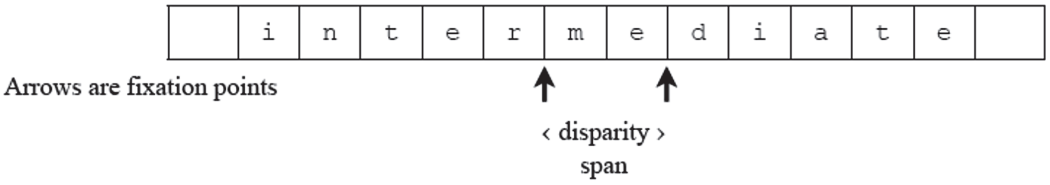
A review of the literature shows that asthenopia, temporal aspects of RD processing, and viewing distance exhaust the case that can be made for specific relative advantages of uncrossed RDs in nonreading tasks. Only asthenopia and viewing distance seem to speak to the task of reading, although not strongly: None of the reported analyses of FD in reading suggest that fatigue plays an important role, and Figure 1 shows that uncrossed FDs pattern with the smaller stimuli that might be expected to make more demands on stereoacuity. How can we account for those data sets that show very substantial proportions of crossed FDs? We now explore the ways in which the perceptual apparatus between the cornea and the cortex—the fovea and the visual pathways—offer real postfusional[12] processing advantages to crossed FDs in reading and play a major role in the theory of foveation that we advance.

## A Model of Binocular Foveation

We have seen that uncrossed FDs can be expected to facilitate binocular fusion in reading, but that they are far from universal in reading (Figure 1). We hypothesize a complementary, postfusional (or nonfusional) processing advantage from *crossed* FDs in reading conditions that do not jeopardize binocular fusion; that advantage is based

on the prioritized processing afforded to the temporal hemifield and nasal hemifovea (e.g., Toosy et al., 2001), which we explore below. We present a model that combines four influences on the quality of the visual input that is presented to postfusional processing (i.e., to word recognition and other aspects of reading): (a) precision of foveal splitting, (b) contralateral preference in the visual pathways, (c) ocular prevalence, and (d) FD. Figure 4 shows details of the projection of the word *intermediate* to the vertically divided human fovea of each eye, with an FD of 2 letters. Crossed and uncrossed versions of the FD are shown in (a) and (b), respectively. Each foveal window receives information from 12 letters—6 to the right and 6 to the left of fixation. Bold type denotes the advantageous contralateral projection from a particular eye to the opposite hemisphere, and regular type denotes an ipsilateral projection. Each eye projects to both hemispheres: The RVF projects to the left hemisphere (LH), and the left visual field (LVF) projects to the right hemisphere (RH). We now introduce the four factors listed above.

**Precision of foveal splitting**. Our theory of foveation proceeds from the fact that the human fovea is vertically divided, projecting to the cerebral hemispheres in the same way as does the extrafoveal retina (Brysbaert, 1994, 2004; Ellis, 2004; Ellis & Brysbaert, 2010; Lavidor & Walsh, 2004; Leff, 2004; McDonald & Shillcock, 2005a, 2005b; Monaghan & Shillcock, 2008; Monaghan, Shillcock, & McDonald, 2004; Shillcock, Ellison, & Monaghan, 2000; but see Jordan & Paterson, 2009). In previous modeling research, we have assumed a simple, precise, vertical split



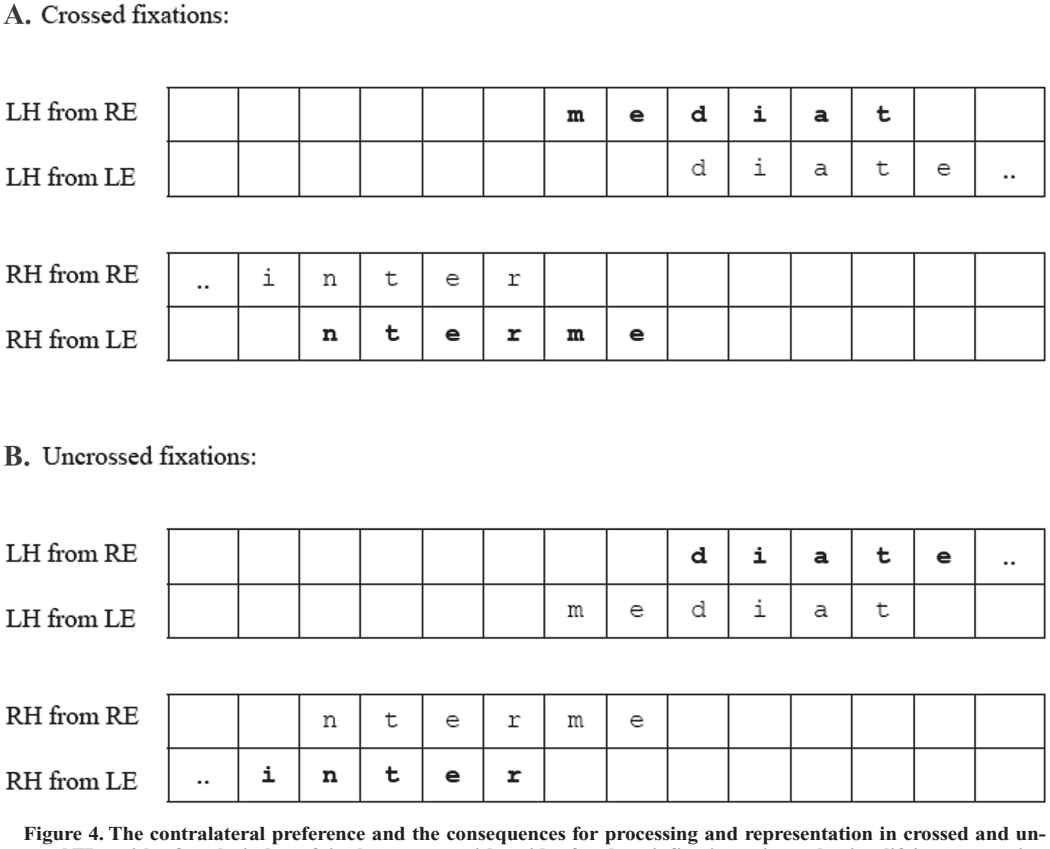




**Figure 4. The contralateral preference and the consequences for processing and representation in crossed and uncrossed FDs, with a foveal window of six characters to either side of each eye's fixation point and a simplifying assumption of uniform acuity within the foveal window. The arrows denote the fixation points of the two eyes. There is an FD of two characters. Bold type denotes prioritized processing due to contralateral projection; ordinary type denotes ipsilateral projection. See the text for details.**

at the foveal midline (see, e.g., Shillcock et al., 2000) in order to explore the implications of the abstract division of input between the two halves of a divided processor. However, the functional anatomy of the human fovea is the focus of continuing research. The issue is the precision of the divided anatomical projection from the fovea, and this question is not straightforwardly settled solely by anatomical investigation, because of the limits on precision of the relevant techniques. Reinhard and Trauzettel-Klosinski's (2003) data suggest individual variation in the precision of foveal splitting, with a majority (two-thirds) between 0º (precise splitting) and 0.3º, and a minority case of an overlap tending toward 0.6º (i.e., a total overlapping section of 1.2º). In Figure 4, we have shown simple, precise, foveal splitting. Below, we will model this range of precision in foveal splitting.

**The contralateral preference**. Contralateral projection is a pervasive principle in the human visual system; the RVF initially projects to the LH, and the LVF initially projects to the RH, in each eye. Toosy et al. (2001) reported finding a neurophysiological bias between these two pathways. They show that monocular Ganzfeld stimulation of one eye causes greater cortical activation in the contralateral hemisphere than in the ipsilateral; the left eye causes more activation in the RH, and the right eye causes more activation in the LH, even though both eyes project to both hemispheres. This observation may reflect a bias at several different levels, as discussed by Toosy et al.: unique contralateral representation of a crescent at the temporal hemifield (Horton & Hocking, 1996), greater retinal ganglion cell density in the nasal hemiretina (corresponding to the temporal visual hemifield; Perry & Cowey, 1985), a bias in favor of crossed fibers at the optic chiasm (Kupfer, Chumbley, & Downer, 1967) and at the lateral geniculate nucleus (Chacko, 1948), organizational bias in the ocular dominance columns in V1 in favor of contralateral input (LeVay, Connolly, Houde, & Van Essen, 1985), and greater contralateral contribution to the activity of V1 cells with a binocular receptive field (Toosy et al., 2001). In short, the human visual system prioritizes processing of the contralateral input at multiple stages, from cornea to cortex. We are currently exploring whether this contralateral preference also applies to foveal processing of orthographic stimuli, using a haploscope to control presentation of the two halves of a word to separate hemispheres (see Obregón & Shillcock, 2007, 2010).[13]

**Ocular prevalence**. The phenomenological prioritization of the signal from one eye over that from the other eye manifests itself as ocular dominance when fusion is impossible or problematic (as in ocular rivalry paradigms) and as ocular prevalence when fusion is assured (Kommerell, Schmitt, Kromeier, & Bach, 2003). Ocular dominance and ocular prevalence are both operationally defined within particular studies, typically using sighting tests and stereoscopic alignment, respectively. In *ocular dominance*, the right eye is more often preferred over the left (40% compared with 20%; Hillemanns, 1927). In *ocular prevalence*, which is more relevant to reading (in which fusion is typically assured), the right and left eyes are equally likely to be preferred in different individuals (Kommerell et al., 2003). Most people exhibit some level of ocular prevalence (Ehrenstein, Arnold-Schulz-Gahmen, & Jaschinski, 2005; Erkelens, Muijs, & van Ee, 1996; Haase, 1995; Heinrich, Kromeier, Bach, & Kommerell, 2005; Jaschinski & Schroth, 2008; Kommerell et al., 2003; Sachsenweger, 1958). What we wish to capture by the term *ocular prevalence* is the "graded quantification of the balance between the eyes" (Kommerell et al., 2003, p. 1397) that is achieved in conditions of fusion with no diplopia; such a quantitative, graded difference in cortical activation has been reported for dominance (Rombouts, Barkhof, Sprenger, Valk, & Scheltens, 1996), at least partly grounded in anatomy and physiology. In the model of foveation in reading reported below, *ocular prevalence* means that one eye will have more effect than the other on cortical representation, even though (unlike the standard operational definition of ocular prevalence) the input from the two eyes is from the same stimulus at the same depth.

**FD**. In the idealized projections, shown in Figure 4, we have assumed a precise foveal split at the fixation point of each eye to emphasize the different patterns of contralateral and ipsilateral projections between the crossed and uncrossed FDs in Figures 4A and 4B. The crossed FD combines two nasal hemifoveal projections at its center (i.e., between the two fixation points, the *disparity span*), via the preferred contralateral channels. The uncrossed FD combines two temporal hemifoveal projections at its center via the dispreferred ipsilateral pathways. The mean size of the disparity span for disparities greater than one character varies between studies, from a minimum of just over one character in Liversedge et al. (2006). Such a figure is the mean of a distribution over all reported participants; the distribution in the general population over all reading conditions will contain larger disparities, necessarily from the large-disparity tail of the distribution and possibly from reading conditions that elicit larger disparities.

**Modeling the visual pathways**. We have motivated the inclusion of four variables in the model: precision of foveal splitting, contralateral preference, ocular prevalence, and FD. Our model of the visual pathways allows us to explore the interaction between these variables in terms of the input to the word-recognition processes. In the model, depicted in Figure 5, each eye is represented by an idealized, one-dimensional retina, in which acuity diminishes linearly with eccentricity (Anstis, 1974; Beard, Levi, & Klein, 1997; Jacobs, 1979; Levi, Klein, & Aitsebaomo, 1985; O'Regan, Lévy-Schoen, & Jacobs, 1983). Text is projected onto this gradient. Contralateral and ipsilateral projections are determined with respect to each retinal midline, and the extent of the bilateral projection resulting from imprecise foveal splitting. These projections are further modulated by the degree of ocular prevalence and by contralateral preference. Representations of the projected text are computed for the left and right hemispheres by fusing the two eyes' projections of the LVF/RH and RVF/LH, respectively. Finally, the two hemispheric representations are fused to form a coordinated interhemispheric representation of the text. We have coined the term *repre-*

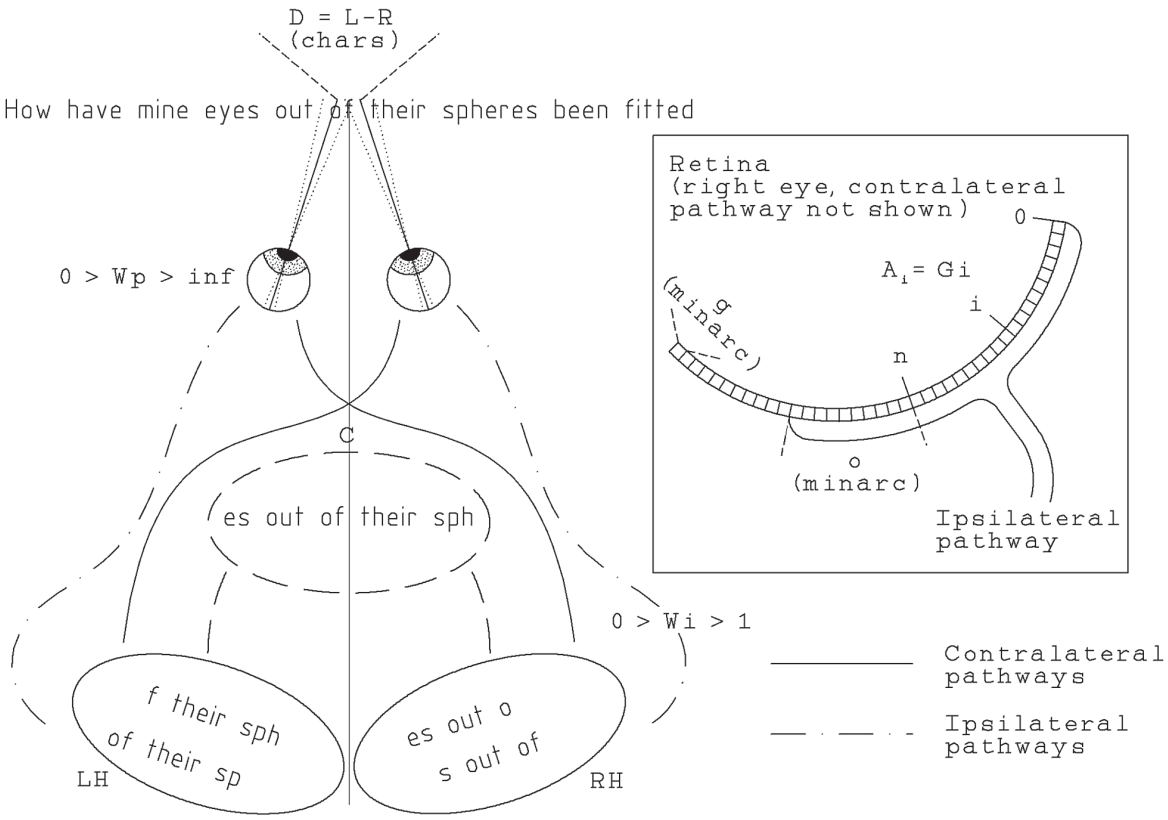



**Figure 5. A model of activation in the visual pathways, elaborating the model in Figure 4. The retina is modeled as a one-dimensional vector of length *n*, with each value representing mean acuity within *g* arc min of distance. Acuity *A* diminishes linearly from the center with gradient *G*. Projection of text onto the fovea is modeled as activation equivalent to the acuity in each division, with activation set to 0 where no text is projected. Ocular prevalence is modeled as a weighting on input through the left eye ($W_p$); values of less than 1 represent right-eye prevalence. Activation is propagated to the cortex via contralateral (e.g., right eye to left hemisphere [LH]) and ipsilateral (e.g., right eye to right hemisphere [RH]) pathways. Temporal activation is transferred ipsilaterally, and nasal activation is transferred contralaterally, with each pathway overlapping the retinal midline by *o* arc min. Contralateral preference is modeled by a weighting on the input through the ipsilateral pathways ($W_i$). Binocular fusion is modeled as occurring in the LH and RH by aligning and summing the separate inputs from the two eyes; fused representations are coordinated in a similar manner (*C*). Variation in FD (*D*), $W_p$, $W_i$, and *o* results in different patterns of activation in the coordinated representation.**

*sentational activation* to describe the numerical distinctions and differences embodied by our model of the visual pathways. This term is intended to be theoretically neutral and can be interpreted in several ways. Since the model begins with the acuity gradient at the retina, one interpretation is that differences in representational activation are essentially differences in acuity, with greater activation being equivalent to greater representational detail. An alternative possibility is that representational activation is simply greater cortical activation, following the finding of Toosy et al. (2001) that greater cortical activation is found in the contralateral hemisphere. Irrespective of precisely what representational activation represents, it is intended that a greater quantity of it provides more useful input to postfusional cognitive processes. In reading, greater representational activation should, therefore, facilitate postfusional processing, *ceteris paribus*.

Our observations concerning the four variables lead to the hypothesis that crossed FDs produce higher representational activation near the points of fixation than uncrossed FDs (cf. Figure 4). Simulations with our model (Figure 5) confirm that this is robustly the case.

## Simulations

Figures 6–9 illustrate the behavior of the model in four sets of simulations. In each graph, the *x*-axis represents the horizontal extent of the word "intermediate," with representational activation on the *y*-axis. Each simulation explores one of the four variables discussed above, and all of the simulations contrast the three types of FD: crossed, uncrossed and conjoint. Nonconjoint FDs are of two characters, except in Figure 9, in which a larger range of FDs is explored. Arbitrary default values of variables shown in Figure 5 were *g* (grain) = 1 arc min and *G* (acuity gradient) = 1. In addition, the length of the vector of values being considered: *n* = 150 (i.e., 2.5º × 60 arc min, the approximate extent of the fovea); *o* (degree of bilateral overlap) = 10 arc min (i.e., 0.15º, the median value of the ma-

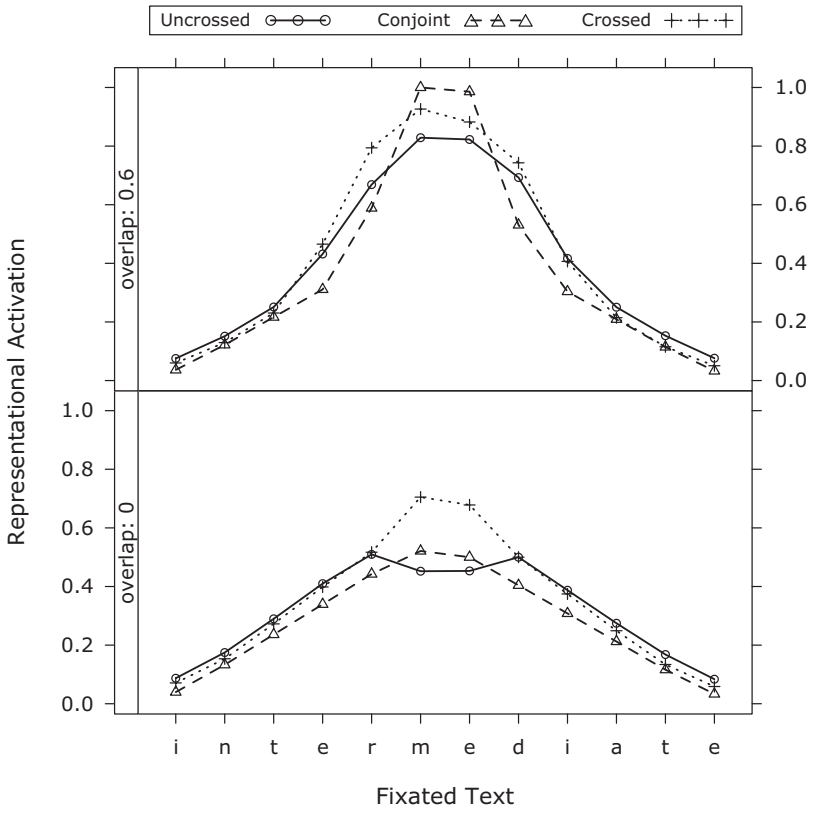



**Figure 6. Qualitative differences among crossed, conjoint, and uncrossed FDs, for zero and 0.6º overlap (i.e., bilateral projection) within each fovea. In this graph and later ones, "representational activation" stands for an unspecified dimension of acuity and/or cortical activation, which facilitates lexical access. $D = \{-2, 0, 2\}$ characters; $W_p = .9$; $W_i = .7$. Minor asymmetries in activation result from ocular prevalence. See the text for details of parameters.**

jority case reported by Reinhard & Trauzettel-Klosinski, 2003); $W_p$ (ocular prevalence) = .9 (weak right-eye prevalence); $W_i$ (contralateral preference) =.7; $D$ (disparity) = {−2, 0, 2} (relatively large, to emphasize differences between crossed, conjoint, and uncrossed fixations). Each character subtended 0.43º. Resolution (of foveal bins to characters), binocular fusion, and coordination were all done by taking mean values. Representational activation is normalized in the range 0–1. See the caption of Figure 5 for more details.

**Precision of foveal splitting**. Figure 6 shows the results of modeling the smallest overlap at 0º (precise splitting, bottom panel) and the largest overlap at 0.6º (i.e., a total bilateral projection of 1.2º; cf. Reinhard & Trauzettel-Klosinski, 2003). When foveal overlap is 0 (precise splitting), the crossed FDs produce better results than do uncrossed FDs within the disparity span, with conjoint fixations producing intermediate results. When bilateral projection is increased, the difference in representational activation between crossed and uncrossed FDs is reduced but spreads outside the disparity span, with crossed FDs still higher. Within the disparity span, activation for conjoint fixations increases to a greater extent than does activation for either crossed or uncrossed fixations.

**Contralateral preference**. The contralateral preference was operationalized as a weight on the ipsilateral pathways in the range $0 < W_i < 1$. Figure 7 compares the effects of three levels of contralateral preference. Variation in the degree of contralateral preference has opposing effects in crossed and uncrossed FDs. A strong contralateral preference ($W_i = .2$, lowest panel) increases representational activation near the points of fixation in a crossed FD, but depresses it in an uncrossed FD. Although less marked, this difference is still apparent, with a relatively weak contralateral preference ($W_i = .8$, top panel).

**Ocular prevalence**. Figure 8 shows a comparison of the effects of three levels of ocular prevalence. Ocular prevalence was operationalized as a weight on the left eye ($W_p > 0$). Strong ocular prevalence tends toward a monocular fixation, the input being dominated by one eye. Thus, the greatest degree of ocular prevalence ($W_p = .1$, lowest panel) diminishes the difference in representational activation between the three fixation types in the disparity span. In addition, the peak of representational activation corresponds to the right eye in the three types of FD (the

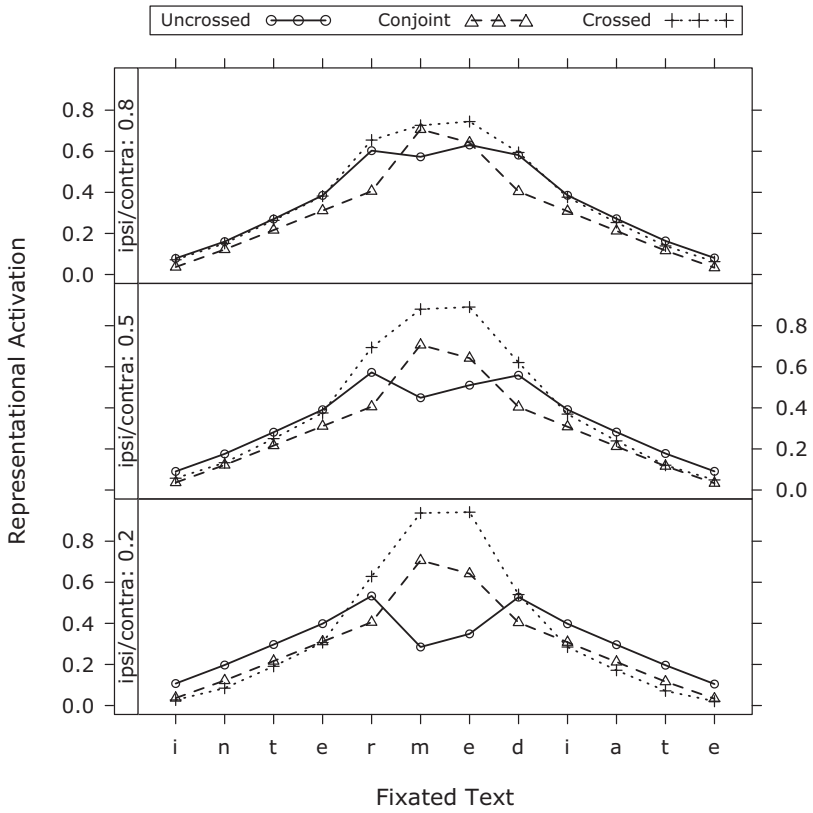



**Figure 7. Qualitative differences among crossed, conjoint, and uncrossed FDs, for differing contralateral preference ratios. $D = \{-2, 0, 2\}$ characters; $W_p = .9$; $o = 10$ arc min.**

opposite pattern would be observed for left-prevalent individuals). Smaller degrees of ocular prevalence ($W_p = .5$, center panel; $W_p = .9$, top panel) introduce further differences and asymmetries between crossed and uncrossed FDs in the disparity span, as the (weak) contralateral preference exerts a more noticeable effect.

**FD**. FD was specified in characters. Figure 9 depicts the variation in representational activation resulting from nine levels of FD. Clear differences between crossed and uncrossed FDs emerge. First, the general level of activation around the eyes' fixation points is substantially greater for crossed FDs. Second, as FD increases within each of the crossed and uncrossed panels, activation begins to fall in the center of the disparity span (as defined in Figure 4). This diminution is to be expected, but these simulations show that it is deeper and appears at smaller disparities in the uncrossed FDs.

A final important aspect of the modeling shown in Figure 9 is that both types of FD (top and bottom panels) produce wider plateaus of higher levels of representational activation than in the conjoint case (albeit there is a dip in the middle of the larger uncrossed FDs). This effect constitutes a general advantage for FDs of both types: FD extends the width of the foveal window by offsetting the foveal windows of the two eyes, so that more of the text falls within high-acuity vision. The direction of the FD determines whether it is the privileged nasal or the nonprivileged temporal hemiretinas/hemifoveas that are overlapped. The implications for reading will be mediated by specific and lexical attentional factors (cf. Henderson & Ferreira, 1990), but one testable prediction is that saccade length should be extended for larger disparities (see Roberts et al., 2010).[14]

In summary, robust processing differences emerge in simulating crossed and uncrossed FDs, reflecting the roles of degree of foveal splitting, of contralateral preference in the visual pathways, of ocular prevalence, and of FD. We have demonstrated that clear and pervasive advantages result from crossed FDs. In all the simulations, only conjoint fixations ever emerged as more advantageous than crossed FDs, and then only in a small minority of simulations. It is worth noting that explicit computational modeling was required to make these complex binocular interactions interpretable; these predicted differences between crossed and uncrossed FDs could not have arisen from ad hoc theorizing.

## Binocular Disparity in Reading

An uncrossed FD impairs fusion less than the same-sized crossed FD does, and conditions in which fusion is difficult produce a greater degree of uncrossed than of crossed FDs. In addition, a combination of established

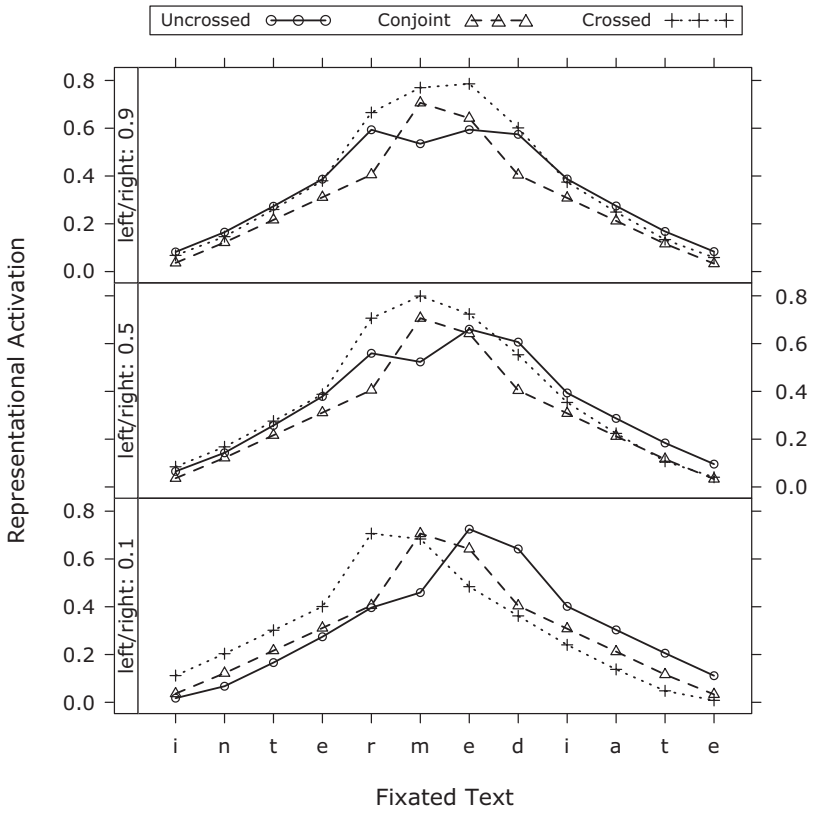



**Figure 8. Qualitative differences among crossed, conjoint, and uncrossed FDs, for different ocular prevalence ratios. $D = \{-2, 0, 2\}$ characters; $W_i = .7$; $o = 10$ arc min.**

findings about the visual pathways suggest that crossed FDs provide a processing advantage in the form of greater representational activation around, and especially between, the points of fixation, as our model illustrates. Our principal claim is that these two observations together explain the variation in FD between the studies of binocular reading shown in Figures 1 and 2. Figure 10 illustrates this idea. Temporal vergence (divergence, uncrossing in reading) is excited by fusion-related activity: When significant effort is expended to ensure binocular fusion or when fusion is uncertain, the saccade generator produces temporal vergence. Nasal vergence (convergence, crossing in reading) is excited by postfusion activity: The more work the processor is required to do, the more it "requests" crossing to alleviate this load.

This model makes several strong predictions about future experimental data. First, it predicts that, when fusion conditions are difficult in reading, more uncrossed FDs will be observed. Further research is required to delineate the conditions that cause fusion difficulty in reading, but work on nonreading tasks, using paragraphs of text as stimuli, has shown that background luminance and text blur increase the tendency toward uncrossed FDs. As noted, we are currently exploring a single case study of the effects of differing illumination on reading (Shillcock et al., 2007). In addition, the effect on FD of the angle subtended by text at the retina is the subject of ongoing investigation (Roberts, Kreiner, Obregón, & Shillcock, 2009; Yen & Radach, 2007); the meta-study reported in Figure 1 apparently shows such an effect. These variables would, therefore, seem to be a good starting point for investigation. Second, the theory predicts that, when fusion is unproblematic, crossed FDs will facilitate lexical processing to a greater degree than will uncrossed FDs. Although straightforward, this prediction will, we suggest, require very careful falsification, given that an extended fixation duration may potentially be caused by problematic fusion processing and/or by problematic postfusion processing, with both of these sources of variation subject to individual differences.

## Discussion

We have tried to address two research communities: the relatively small one concerned with binocular reading and the large vision science community concerned with binocularity in general and with vergence and depth perception in particular. To clarify our position, we summarize it as follows:

1. The pervasive departures from exactly conjoint binocular fixations in reading should not simply be dismissed as error or noise; rather, such absolute disparities, or "overall disparities" (Howard & Rogers, 1995, p. 243),

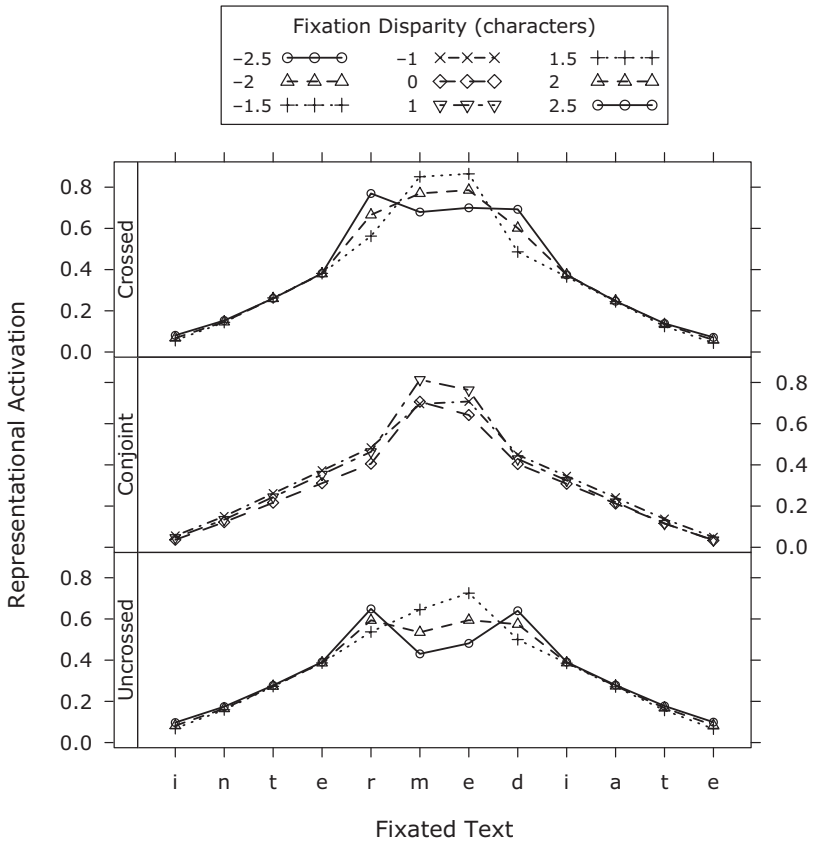



**Figure 9. Qualitative differences among crossed, conjoint, and uncrossed FDs, for different binocular disparities. Positive numbers refer to crossed FDs ($W_p$ = .9, $W_i$ = .7, $o$ = 10 arc min).**

in reading can be interpreted as adaptive, regardless of their origin.

2. Such interpretations are required for both directions of horizontal departure (i.e., right eye's fixation point to the left or right of the left eye's fixation point on the text) from exactly conjoint binocular fixation. These interpretations need to be congruent with the substantial existing data for nonreading as well as reading tasks.

3. Placing the intersection of the principal visual axes, or lines of sight, in front of the text or (virtually) behind the text, respectively, has the effect of placing the text behind or in front of the horopter.

4. These two regions (behind or in front of the horopter) are associated with different behaviors in depth perception, with the coordination of retinal images from objects away from the horopter; we update Mustillo's (1985) little-cited review of processing in the two depth-perception regions.

5. Although absolute disparity (or *overall disparity*, the angle between the two principal visual axes) is not understood to be used on its own to gauge depth accurately for a single point, the core behavior of the eyes is their ability to converge on an isolated point, meaning that information about absolute disparity is available. Indeed, V1 binocular neurons specialize in absolute, not relative, disparity.

6. The general absence of depth in reading (i.e., relative disparity between points at different depths) does not mean that the resources and mechanisms associated with binocular depth processing are not available and are not engaged. The computational problem of depth perception is one of coordination of the images on the two retinas.

7. Both eyes contribute in binocular reading; monocular reading is less effective.

8. Reading requires the coordination of visual information on the two retinas. Our review of the depth perception literature confirms that there is robustly better coordination in depth perception when relative disparity involves one direction of departure from conjointness—that is, for the images of an object between the viewer and the horopter (crossed RD). This advantage is equivalent to a processing advantage for noncorresponding images in reading in which the left eye's fixation point is to the left of the right eye's fixation point (uncrossed FD).

9. A different processing advantage for images in the *other* direction of departure from exactly conjoint binocular fixation (left eye's fixation point to the right of the right eye's fixation point) is suggested by computational modeling that we report, involving a range of physiological and anatomical influences between the cornea and the cortex.

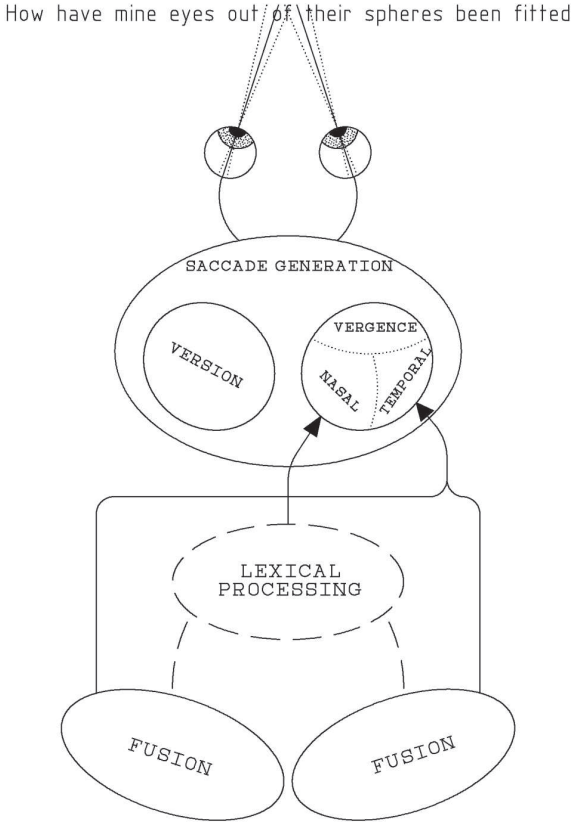



**Figure 10. Schematic model of binocular fixation in reading. Temporal vergence (divergence) in saccade generation is excited by hemispheric fusion processes; problematic fusion may be offset by creating uncrossed FDs. Nasal vergence (convergence) is excited by activity in postfusion processing; higher cognitive processing, such as the requirement to expand the perceptual span to accommodate more words, may precipitate crossed FDs.**

10. We relate the two different advantages described in Points 8 and 9 with stimulus conditions reported in the literature. This is formalized in a model of how the two eyes foveate text in reading.

We have argued for a particular interpretation of binocular foveation behaviors on the basis of the existing literature on depth perception and on the processing implications of the visual pathways. We have formulated these interpretations in terms of the combination of the influences of binocular FD, ocular prevalence, contralateral preference, and degree of foveal bilateral projection (Figure 5) and in the hypothesized relationships between divergence and fusional processing difficulty and between convergence and postfusional processing difficulty (Figure 10).

A methodological assumption in this theorizing has been that unexpected behavioral data (such as the very existence of binocular FD) may be in some way adaptive, rather than being solely the result of "noisy" processing in the reader, of artifact in the equipment, or of experimenter error. We have shown ways in which binocular FD can be adaptive, both in its size and direction (crossed or uncrossed).

Our theory of binocular foveation has shown that it is possible to see binocular vision not primarily in terms of the problems of alignment and correspondence but rather, in terms of a remarkable flexibility in responding to variation in the visual input. An important principle here is that the visual system achieves this flexibility by a peripheral mechanism of vergence: Converging or diverging the eyes tips the visual system into different modes of operation, taking advantage of different processing domains within the visual system. A problem of optimizing the processing of the visual input is solved in a mechanical, embodied manner, as opposed to one that is purely abstract and computational.

The theory of binocular foveation we have presented makes a number of empirical predictions that require careful testing. These predictions are probably better assessed by large corpora of naturalistic eye movements than by factorial experiments. Two principal issues militate against reliance on factorial experimentation and in favor of the greater statistical power available from large corpus analysis: the impossibility of manipulating disparity directly as an independent variable in text reading and the complex confounds introduced by the interconnection and intercorrelation of the various factors that affect binocular eye movements in reading.

We have shown that binocular FD may be seen as integral to normal reading, with specific behaviors that are interpretable as adaptive. This theory of binocularity presents a challenge to researchers modeling eye movements in reading, either to accommodate binocularity into implemented models of reading or to show that binocular data are lost to the reading system relatively peripherally and, therefore, become irrelevant to the central execution of reading.

## Conclusions

Solving the correspondence problem—achieving fusion—is of prime importance in reading, as it is in other binocular tasks. The correspondence problem elicited by binocular FDs in reading resembles aspects of the correspondence problem found for the images of objects in front of or beyond the horopter: The two images are offset in one or other direction. Crossed RDs in depth perception resemble uncrossed FDs in reading, and uncrossed RDs in depth perception resemble crossed FDs in reading.

The fusion-related processing of crossed RDs is more effective and robust than is the comparable processing of uncrossed RDs, in development, in impairment, and over a range of behaviors elicited in experiments on normal adult participants. Uncrossed FDs are, therefore, expected to be the default direction of FD when the stimulus configuration is perceptually challenging and stereofusion is problematic.

When the overall stimulus configuration is not perceptually challenging and stereofusion is assured, then more effective non-fusion-related processing can be achieved by making maximal use of the nasal hemifoveas—as occurs in a crossed FD—reflecting foveal splitting and the contralateral preference.

Binocular FD in reading allows a coherent extension of the split-fovea model of reading. It does not militate

against the split-fovea theory or make the theory irrelevant to reading, as some researchers have recently suggested.

This theory currently offers the only explanation for the emerging data on binocularity derived from eyetracking and dichoptic presentations. Such data challenge all current models of reading, opening exciting theoretical possibilities.

## AUTHOR NOTE

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## NOTES

1. We use the term *disconjugacy* only when we also consider the saccade.

2. We thank a reviewer for pointing up this issue. The precise implications of binocular versus monocular calibration are unknown and likely to be complex, but we suggest that binocular calibration is conservative, overall, with respect to binocular FD, in that a possible binocular FD is effectively being "zeroed" by a binocular calibration, so that any subsequent nonzero FDs of the same sign underestimate the objective disparity.

3. There are two aspects to this difference between sentential and paragraph materials. The first is the degree to which the fixation stimulus at the beginning of a trial requires a precisely conjoint fixation and how frequently this requirement is reinforced during the experiment. The second is less easily specified, but Radach, Huestegge, and Reilly (2008) have demonstrated the importance of this difference in materials for monocular eye movements. Heller and Radach (1999) reported that disparity increases during the reading of a line, as did Nuthmann and Kliegl (2009). This effect is also present in our own corpus data, as is an increase in disparity over successive lines of text in the same paragraph.

4. Angle subtended by each letter is just one of the variables suggested by Nuthmann and Kliegl (2009); we have selected this variable simply as a convenient proxy for legibility. We will go on to claim that uncrossed FDs in reading are prompted by conditions that make binocular fusion difficult.

5. The optometric prefixes *eso-* ("in") and *exo-* ("out") may also be used, respectively, to refer to the overconverged and underconverged states being referred to here as "crossed" and "uncrossed" binocular fixations on the text.

6. Although we have used the standard term RD in our discussion of the stereopsis literature, FDs naturally have retinal implications; indeed, the key point we will make is that we can understand the retinal implications of FDs in reading in terms of the processing of RDs in depth perception.

7. Indeed, in real-world fixation behavior, we may extend this description to say that noncorrespondence between the retinal images caused by the structure of the visual scene in depth and by nonconjugate saccadic movements and fixations is also typically copresent.

8. Albeit with some ranking, that means that contour will typically be more influential in binocular fusion in any conflict with accommodation and vergence information (see, e.g., Bruce, Green, & Georgeson, 1996, p. 138; Foley, 1980; see also Alais & Blake, 2005).

9. We will not pursue the suggestion, briefly considered by Mustillo (1985), that conjoint fixations may access a third processing domain.

10. N.B.—Our claim is not that there is perceived depth in normal reading; we clearly do not see depth comparable to that elicited by haploscope-induced disparity, for instance. However, the absence of any phenomenological depth in the experience of reading is a moot point; anecdotally, the so-called "plastic effect" (see, e.g., Schlosberg, 1941) does seem to obtain in reading, for instance.

11. Data available on request, along with that from six normal readers who showed no effect of room illumination.

12. We have made the distinction between *fusion-related processing* (facilitated by uncrossed FDs) and *postfusional processing* (facilitated by crossed FDs), but the latter term reflects our interest in the eventual reading behaviors and might also have been termed "processing not directly connected with fusion," given that it includes such factors as the projection of visual information from the retina.

13. Data available on request.

14. One reviewer has suggested that larger FDs should be predictive of shorter fixation times in normal reading. We do not believe that such a simple prediction will be confirmed and have found no evidence in our data that it is true; Liversedge and Blythe (2009) have reported the absence of such an effect in their own data. We suggest that FDs of different sizes and signs correlate with different styles of hemispheric processing. We have said that greater representational activation should facilitate postfusional processing, *ceteris paribus*. Our prediction is that what we have called representational activation will have more effect on lower level perceptual processing than on the higher level cognition that is reflected in fixation durations. Extending the window onto the text (by widening FD) might involve similarly spreading out the constant processing resources more thinly (cf. Henderson & Ferreira, 1990), so that any advantages of a wider window onto the text are offset by having more work to do with the same resources.

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